RTCA Free Flight Select Committee
Safe Flight 21 Steering Committee

Eurocontrol ADS Programme

ADS-B Technical Link Assessment Team (TLAT)

Technical Link Assessment Report

March 2001

Contents

1. Introduction

This report summarizes the technical assessment of candidate ADS-B/situational awareness links commissioned by both (1) the Safe Flight 21 (SF21) Steering Committee consistent with the recommendations of the RTCA Free Flight Select Committee and (2) the Eurocontrol ADS Programme Steering Group (PSG). The report builds upon the November 1999 Phase One Report [Ref. 1] developed by a precursor to the TLAT, the SF21 Technical ADS-B Link Evaluation Team.

1.1 TLAT Objectives and Membership

The SF21 Steering Committee and Eurocontrol ADS PSG requested continued technical evaluation of three ADS-B and situational awareness link candidates, 1090 MHz Extended Squitter, VHF Digital Link (VDL) Mode 4, and Universal Access Transceiver (UAT). The candidate links were to be technically characterized in a common manner and evaluated, in a reference set of traffic scenarios, to a common set of technical link assessment criteria derived from the need to support both the Free Flight Operational Enhancements [Ref. 2] specified in August 1998 by the RTCA Free Flight Select Committee and further applications as designated by the Eurocontrol ADS PSG. The Terms of Reference for the TLAT are Appendix A to this report.

The TLAT began its activities in May 2000. The roster for the Team and a list of additional contributors to TLAT activities are Appendix B to this report. Subject matter experts for each of the three ADS-B link candidates have participated, as have key technical personnel from several organizations within the FAA, Eurocontrol, and from Johns Hopkins University, the Mitre Corporation, and the industry.

1.2 Scope of this Report

This report discusses the technical assessment approach taken by the TLAT, summarizes TLAT simulation/analysis results, and presents TLAT findings. The TLAT understands that this report is intended to serve as a primary technical input to FAA and Eurocontrol selections of ADS-B link technologies for implementation. It must be emphasized that these selections of ADS-B link technologies will be based a number of considerations (e.g., cost/benefit and institutional/ transitional issues) in addition to the technical factors discussed herein.

This report does NOT contain an ADS-B link recommendation.

Section 2 of this report provides an overview of the three candidate ADS-B/situational awareness links. Section 3 discusses the Technical Link Assessment Criteria approved by the SF21 Steering Committee and the Eurocontrol ADS PSG and the traffic scenarios developed by the TLAT and approved by the SF 21 Steering Committee and the Eurocontrol ADS PSG. Section 4 discusses the technical assessment approach taken by the TLAT. Section 5 summarizes TLAT findings and areas for potential further study. Appendices to the report provide detailed system descriptions of the candidate links and significant supporting information for the Technical Link Assessment Criteria, traffic scenarios, and TLAT simulations/analyses.

2. Overview of ADS-B/Situational Awareness Link Candidates

The TLAT has been asked to evaluate three candidate links. Two of these links, 1090 MHz Extended Squitter and UAT, are wide-band links operating in the L-Band. The third, VDL Mode 4, is implemented using multiple narrow-band channels in the VHF Band. A one-page summary table of technical characteristics of the three link candidates is included as Appendix C. System descriptions of each of the three candidates, for link evaluation purposes, have been prepared by respective subject matter experts (Appendices D, E, and F). While these system descriptions have been reviewed by the TLAT and many TLAT comments have been incorporated, the development of the system descriptions has been the responsibility of the subject matter experts.

2.1 1090 MHz Extended Squitter

The 1090 MHz Extended Squitter has been developed as an extension of Mode S technology widely used for aeronautical secondary surveillance radar applications. Each extended squitter message consists of 112 bits, 24 bits of which are used for parity. The data rate used is 1 megabit per second, within a message. Access to the 1090 MHz channel is randomized, and the channel is shared with current Air Traffic Control Remote Beacon System (ATCRBS) and Mode S responses to interrogations from ground-based radars and TCAS. The squitters proposed for ADS-B are "extended" in the sense that prior Mode S squitters contained 56-bit messages.

1090 MHz Extended Squitter message formats for ADS-B and transmission rates have been defined in detail by the ICAO Secondary Surveillance Radar Improvement and Collision Avoidance System Panel (SICASP), in conjunction with RTCA Special Committee 186 and EUROCAE Working Group 51. A joint RTCA/EUROCAE ADS-B MOPS for the 1090 MHz Extended Squitter [Ref. 3] was approved by those standards bodies in September and October 2000, respectively. Augmentation to the MOPS and ICAO standards (SARPs) is in progress to describe techniques to enhance the range of the Extended Squitter system and to support TIS-B. The TLAT evaluated the Extended Squitter system as it is expected to be defined by the augmented MOPS and SARPs. Additional message formats have been proposed by 1090 MHz Extended Squitter subject matter experts to support FIS-B.

Appendix F is a description of the 1090 MHz Extended Squitter system evaluated by the TLAT.

2.2 Universal Access Transceiver (UAT)

The UAT was developed under an Independent Research and Development (IR&D) project at the Mitre Corporation. UAT is a "clean sheet" design optimized toward the support of broadcast applications, both air- and ground-based, to support surveillance and situational awareness. The UAT data rate is approximately 1 megabit/second within a message. Access to the UAT medium is time-multiplexed within a 1 second frame between ground-based broadcast services (the first 188 milliseconds of the frame) and an ADS-B segment. While the design presumes time synchronization between ground-based broadcasts to reduce/eliminate message overlap, medium access within the ADS-B segment is randomized. Initial UAT operations have been conducted using the experimental frequency of 966 MHz. Operational demonstrations in Alaska are using 981 MHz as the UAT frequency.

UAT MOPS development within RTCA was initiated in December 2000. FAA intends to propose UAT SARPs development in ICAO pending U.S. inter-agency coordination.

Appendix D is a description of the UAT system evaluated by the TLAT.

2.3 VHF Digital Link (VDL) Mode 4

VDL Mode 4 technology has been under development since the late 1980's, initially in Sweden but more recently in a number of States. VDL Mode 4 uses two separate 25 KHz Global Signalling Channels (GSCs), with additional channels used in areas with medium to high aircraft density. Access to the VDL Mode 4 medium, within a channel, is time-multiplexed, with a data rate of 19.2 kilobits/second within a message. Various types of prototype single-channel VDL Mode 4 equipment have been fielded since 1991. More recently, prototype dual-GSC equipment has been demonstrated and evaluated in Italy.

While VDL Mode 4 technology has been proposed and demonstrated for a wide variety of aviation applications, including two-way aeronautical telecommunications and local area augmentation to GNSS, the TLAT, as directed by the SF21 Steering Committee and the Eurocontrol ADS PSG, has evaluated all candidate links solely with regard to their ability to support ADS-B, TIS-B, and FIS-B (see Section 3).

VDL Mode 4 Standards and Recommended Practices (SARPs) have been developed by the ICAO Aeronautical Mobile Communications Panel (AMCP) and approved by the ICAO Air Navigation Commission in December 2000. Additionally, a EUROCAE MOPS for VDL Mode 4 airborne equipment is nearing completion. Also, a European Telecommunications Standardization Institute (ETSI) standard for VDL Mode 4 ground-based radios is being circulated for public comment.

Appendix E is a description of the VDL Mode 4 system evaluated by the TLAT. The TLAT notes that two approaches to the management of multiple (greater than three) VDL Mode 4 channels have been proposed when the VDL Mode 4 system is applied to high density future air traffic scenarios. The TLAT has evaluated both approaches through analysis and /or simulation.

3. TLAT Evaluation Criteria for ADS-B/Situational Awareness Links and Traffic Scenarios

3.1 Evaluation Criteria

The TLAT link evaluation criteria provide the metrics by which the ADS-B/situational awareness link candidates have been assessed. These criteria include the criteria originally developed by the SF21 Link Evaluation Team (LET), additional criteria proposed by Eurocontrol, and other considerations specified in the TLAT Terms of Reference (TORs). This report is intended to document the performance of the candidate datalinks in relation to the different criteria (both old and new) and to provide the ability to assess technical aspects of the various options.

3.1.1 LET Criteria

The LET developed a set of technical link performance criteria to evaluate the candidate ADS-B/ situational awareness links. These were based primarily upon two industry-consensus RTCA documents:

- the Joint Government/Industry Plan for Free Flight Operational Enhancements (the "Free Flight Operational Enhancements Document"), dated August 1998 [Ref. 2], and
- the ADS-B MASPS, RTCA DO-242 (the "ADS-B Minimum Aviation System Performance Standards"), dated February 1998 [Ref. 4].

Using the description of the nine operational enhancements defined in the Free Flight Operational Enhancements Document, the LET determined that all link-related requirements in the ADS-B MASPS were applicable to the evaluation of the links. Excerpts from the ADS-B MASPS that summarise these requirements are included within Appendix G of this report.

Furthermore, the consideration of the above operational enhancements made it clear that requirements relating to support of Traffic Information Service-Broadcast (TIS-B) and Flight Information Service-Broadcast (FIS-B) services need to be taken into account in order to support the identified operational enhancements. These requirements are not covered in the ADS-B MASPS and there are no established standards as yet for these services. Therefore, the LET developed additional performance criteria for TIS-B and FIS-B. The development of TIS-B and FIS-B link evaluation criteria by the LET should NOT be viewed as a statement that these services must necessarily be provided on the same radio frequency link as is ADS-B. Additionally, the TLAT recognizes that these TIS-B and FIS-B link evaluation criteria are necessarily hypothetical and may NOT reflect the systems that will be implemented.

The LET also decided that in addition to the ADS-B, TIS-B and FIS-B related criteria, there should be some "implied" criteria that need to be considered in order to evaluate comprehensively the candidate links and provide the complete picture. Two categories of such criteria were identified assessing the overall implementation feasibility and maturity and the integration/interoperation of the candidates with existing systems.

It is important to note that the LET criteria did not include considerations for the provision of Differential GNSS (DGNSS) or two-way (including air-to-air) addressed aeronautical communications services over the ADS-B/Situational Awareness link. While these services are very important in the complete picture of the aircraft equipage and they should be considered in the overall aircraft architecture, TLAT concentrated on ADS-B/situational awareness and directly linked issues.

3.1.2 Additional Criteria and Requirements

In addition to the above LET criteria, the TLAT used further criteria - approved by both the SF21 SC and the Eurocontrol ADS PSG.

3.1.2.1 Eurocontrol Criteria

The further criteria from Eurocontrol stem from European ADS requirements development that has occurred subsequent to the adoption of the ADS-B MASPS by RTCA. The ADS-B MASPS could not be endorsed by EUROCAE because European ADS requirements were not sufficiently mature. The Eurocontrol criteria are being considered for incorporation in the ADS-B MASPS by the SC-186 working group formed to update the MASPS.

Since the European ADS-B requirements are not yet finalised, the Eurocontrol criteria represent a snapshot of the ongoing discussions in Europe in relation to ADS-B requirements. These criteria aim to assess the margin that the candidate datalinks are able to provide to allow for the fulfilment of potential additional or differing ADS-B requirements. The assessment of this margin, if any, is an important element of any link decision, as it can safely be assumed that the ADS-B system as currently envisaged may differ from the implemented system.

The Eurocontrol criteria cover two air/ground surveillance scenarios expected to be implemented in Europe. The first scenario is the overlay of monopulse Secondary Surveillance Radar with ADS-B, where the latter serves as gap filler and also supplies trajectory intent information. This first scenario is applicable to airspace of medium and low-density traffic. The second scenario is the overlay of Mode S Enhanced Surveillance services with ADS-B, where ADS-B provides state vector and trajectory intent information as well as serves as a gap filler for enhanced surveillance. This second scenario is applicable to airspace of high-density traffic (e.g., Core Europe).

In addition, the Eurocontrol criteria extend the requirements for long-range deconfliction applications. These extended requirements are applicable to all European free flight airspaces (including Core Europe).

These additional Eurocontrol criteria provide air/ground scenarios (not in the ADS-B MASPS) to TLAT considerations. In addition, these criteria dictate an extended range requirement for the air/air case and the provision of two additional (four in total) Trajectory Change Points (TCP) for both the air/ground case and the air/air case. Detailed information on the criteria is provided in Appendix G.

3.1.2.2 Further Criteria from the TLAT Terms of Reference

Furthermore, the TORs of the TLAT required the group to develop criteria to evaluate the candidate datalinks against some issues that are not covered by the criteria described previously. Specifically, the TORs require the TLAT:

- to evaluate the technical aspects of using multiple ADS-B datalinks potentially in different airspace or aircraft types
- to identify and evaluate any link dependent criteria originating from operational safety assessments
- to assess the expandability and excess capacity of the candidate datalinks.

3.1.3 Summary of Evaluation Criteria

3.1.3.1 Technical Performance Criteria

The ADS-B MASPS requirements for ADS-B air-to-air surveillance range, report update interval, and report accuracy are used to assess how the candidate links perform in relation to the free flight operational enhancements (including the "simultaneous approach" application referenced in the ADS-B MASPS) identified by the SF21 Steering Committee. These requirements specify the minimum range for acquisition of the state vector, the mode-status and the on condition report where applicable, as well as the maximum update period.

The Eurocontrol criteria augment those of the ADS-B MASPS with specific air/ground performance characteristics. These air/ground criteria specify ranges, use of intent information (TCP), additional ADS-B information elements (such as Controller Access Parameters) and update times. Additionally, Eurocontrol criteria extend existing ADS-B MASPS air-to-air requirements for long range deconfliction and increase the number of TCPs to be reported.

TIS-B has been considered by the TLAT in the context of encouraging ADS-B equipage by providing TIS-B reports only on non-ADS-B targets. In this context, the TLAT believes that the capacity impact of TIS-B implementation is less than that of ADS-B equipage by all aircraft. Therefore, the TLAT concluded that separate simulation of TIS-B impact on candidate link capacity is unnecessary. As the TLAT used the ability of a candidate link to support TIS-B as an evaluation criterion, specific details of TIS-B implementation are included in each candidate link system description.

For FIS-B, a datalink loading for evaluation purposes was developed by the LET based upon a prioritised listing of FIS-B information exchange requirements provided by the SF21 Steering Committee. The TLAT modelled the FIS-B impact on the channel as 200 bits per second per ground station. At the direction of the SF 21 Steering Committee and the Eurocontrol ADS PSG, the TLAT has assessed FIS-B only within the context of U.S. traffic scenarios.

3.1.3.2 Additional Implementation and Institutional Criteria Involving Technical Judgement

The additional link evaluation criteria, which address implementation and institutional issues and which involve technical judgement, are as follows:

- Time to implementation
- Time to Availability of International Standards
- Time to RF Spectrum Availability
- Status of reduction to practice: Implementation Risk/Complexity
- Ability to Integrate and Coexist with Existing Systems
- Ability to Mitigate Potentially Catastrophic Issues Raised in the ADS-B Operational Safety Assessment [Ref. 5].

Assessment of the candidate links against these criteria is made using a combination of modelling results and engineering judgement. Although universal equipage on a single agreed link is most desirable, multi-link equipage may be of interest to some states in order to encourage voluntary equipage by different user groups or to accommodate possible limitations in one alternative with complementary capability from another link. Criteria for multi-link use are not addressed in this report; however, Appendix L reviews certain multi-link alternatives with associated interoperability and incremental cost considerations.

The TLAT Evaluation Criteria of the candidate links and their derivation are discussed in detail in Appendix G.

3.2 Traffic Scenarios

The traffic scenarios are important to put into perspective the performance that the candidate links will achieve in a realistic environment. They describe the physical distribution of aircraft that must be considered in the simulations, which will complement the other investigation in lab and flight-testing.

TLAT agreed on three traffic scenarios to be used in its technical evaluation of the candidate links. Table 3-1 summarises the characteristics of these traffic scenarios.

Scenario	Total Aircraft	Scenario Area
LA Basin 2020 (LAX)	2694 (50 percent increase over estimated 1999 traffic levels) (including 225 on the ground)	400 nmi radius
Core Europe 2015 (XCE)	2091 aircraft (73 percent increase over estimated 1999 traffic levels) (including 150 on the ground)	300 nmi radius
Low Density	360 (all airborne)	400 nmi radius

Table 3-1: Selected Traffic Scenarios

In its November 1999 Report [Ref. 1], the LET had selected two additional traffic scenarios: the LA Basin 1999 and the Core Europe 2005 scenarios. The TLAT, for reasons of time, decided to evaluate only the three scenarios in Table 3-1. These scenarios are sufficient to show the performance of the candidate links in the time frame and the operational environments of interest.

The LA Basin 2020 scenario was generated using as a baseline the LA Basin 1999 scenario with the aircraft densities increased by 50 percent. The LA Basin 2020 scenario has 471 aircraft within 60 nmi of the scenario's centre (this includes aircraft on the ground). There are 1181 airborne aircraft within a radius of 225 nmi and a further 1289 airborne aircraft between 225-400 nmi. Around ten percent of the total number of aircraft is above FL 100.

The Core Europe 2015 scenario assumes a traffic increase of 73 percent in comparison to 1999 traffic levels and is focused around five major Terminal Maneuvering Areas (TMAs) in the busiest European area (Brussels, Amsterdam, London, Paris, and Frankfurt) with the Brussels TMA in its centre. Superimposed over the aircraft associated with each TMA, is a set of airborne en route and TMA aircraft. The 2015 scenario has 157 aircraft (25 on the ground) within a radius of 50 nmi from each TMA. There are 696 en-route aircraft within 200 nmi from the centre and an additional 585 aircraft (150 in TMAs) between 200-300 nmi. There are also 25 aircraft on the ground in the whole of the area. Approximately sixty-five percent of the total number of airborne aircraft are above FL 100.

The low-density scenario has been developed by scaling downward the LA Basin scenario. It comprises 360 aircraft uniformly distributed over a circle of 400 nmi radius. All aircraft are above FL 250.

More detailed information on the scenarios considered by TLAT may be found in Appendix H.

4. Technical Assessment Approach

The primary objective of the technical assessment of the ADS-B data link candidates is to characterize the performance of each link with respect to the technical performance criteria described in section 3.1. Link performance characterization is based on a modeling and simulation process, which uses laboratory bench and field/flight test data to validate, where possible, receiver performance and simulation models. The process and its inputs are illustrated in Figure 4-1.

The traffic scenarios and operational environment represent a series of assumptions regarding the disposition of aircraft and ground systems that must be considered in the link characterization. For example, the traffic scenarios dictate the number of aircraft in a given volume of airspace, their altitudes and their equipage. Traffic scenario assumptions are documented in Appendix H. With regard to the operational environment, interrogator databases have been provided for future high density scenarios in order to model interference on 1030 MHz and 1090 MHz pertinent to the operation of the 1090 MHz Extended Squitter and UAT. Additionally, the impact of TCAS operation and conservative estimates of DME interference have been incorporated into the modeling of the L-Band links.

The receiver/waveform model relates a signal, noise and co-channel interference types and levels at the input to a receiver to a probability of successful message receipt. The simulation model for each link invokes the receiver/waveform model to estimate the performance of the RF link between each pair of aircraft. The simulation model keeps track of aircraft, estimates ranges and timing between communicating (or interfering) pairs of aircraft, generates the received signal and interference power levels for the aircraft and determines the measures of performance. The measures of performance can then be directly compared to the evaluation criteria to complete the link characterization. Both receiver and network models are discussed in section 4.1 while the test data used to compare with results from the models are discussed in section 4.2. The TLAT believes that multipath will cause significant effects, especially on an airport surface. For practical reasons, these effects are not represented in the simulations (see Appendices M.6 and N.1).

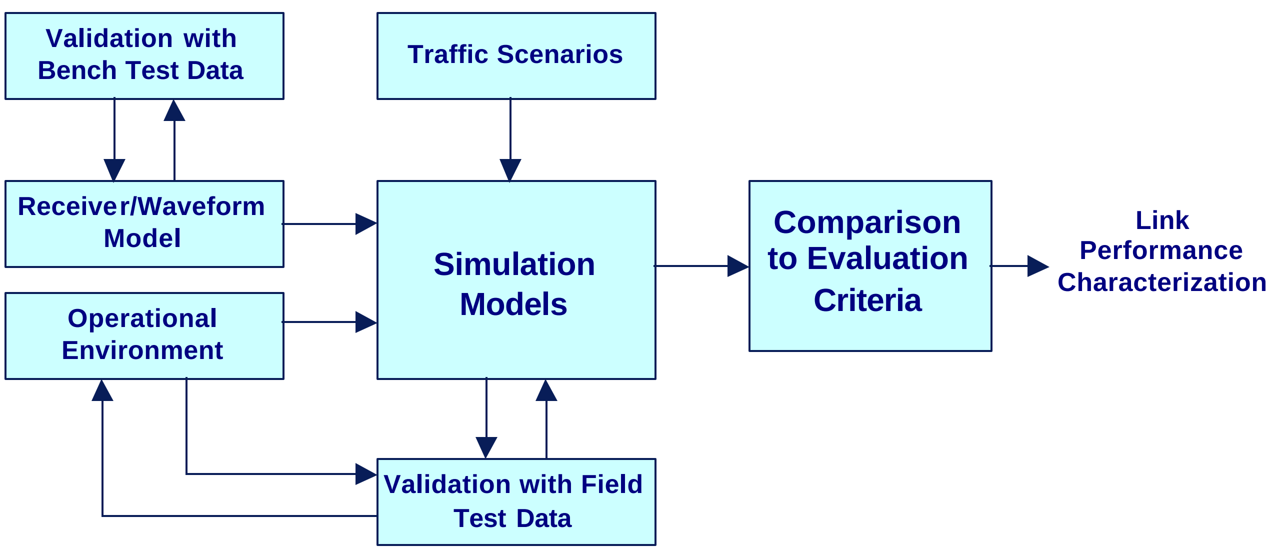

Figure 4-1: Technical Evaluation Approach Overview

4.1 Simulation Tools

There are two types of models required to complete the link characterization: receiver/waveform and full-scale simulation. There are three separate receiver/waveform models employed in the link evaluation, one for each link. All of the receiver/waveform models are based on bench test data taken by Johns Hopkins Applied Physics Laboratory (APL) on the UPS Aviation Technologies supplied radio equipment supplied for Ohio Valley SF21 Operational Evaluations. Bench test data provides the most accurate characterization of actual link equipment; however, it also introduces the effects of specific implementation choices, which may not be generally representative of the radio performance once large scale deployment has occurred. Therefore, the receiver/waveform models used in the link characterization have been designed to account for generalized implementations and thus have reduced the impact of certain implementation choices (e.g., signal acquisition process).

For each link's receiver/waveform model, there is one or more corresponding customized simulation models. The goal in the development of the simulation models was to maintain identical inputs and treatments of the three links. For example, each of the simulation models computes the signal levels at the victim receiver of all ADS-B messages transmitted by the other aircraft in the same way, including antenna gains (based on the model described in Appendix I) and propagation loss. However, because of the links' differing designs, the simulation models for each link are required to address somewhat different aspects of operation in order to focus on the issues that most critically affect performance. Table 4-1 lists the major functions collectively addressed by the simulation models and the links to which these functions are primarily applicable in order to assess performance adequately.

Functions	Links for Which Function Applicable
Traffic Distribution	All
Multiple Channel Management	VDL Mode 4
Co-site adjacent channel interference	All*
Pair-wise signal strength estimation (including LOS geometry, range, and antenna gain variations)	All
Co-channel (self) interference	All
Co-channel (other system) interference	Extended Squitter
Self-organizing slot selection logic	VDL Mode 4
Random Access	Extended Squitter, UAT

***For interference to VDL Mode 4 from voice transmissions, see also Appendix N.5.

Table 4-1: Major Functions Addressed by Simulation Models

One Extended Squitter simulation model is based on a 1090 simulation effort performed at the Volpe National Transportation System Center, which had originally been geared towards the evaluation of the effects of ADS-B on a radar interrogator. The simulation has been adapted to examine the effects of the 1090 MHz environment on ADS-B message reception. This model now produces a data stream representing a time sequence of arrival at the victim receiver of the ADS-B messages, along with both co-channel and adjacent channel (1030 MHz and 1090 MHz) interference. This data stream is then fed through a second simulation model, developed at APL, which adds other interference, including FIS-B transmissions from the ground; computes signal and interference levels as described above; and uses the receiver performance model to convert this information to a probability of successful message receipt for each ADS-B message. A second Extended Squitter simulation model has been developed at DERA in the United Kingdom, and is being used to evaluate 1090 MHz performance in the future Core Europe traffic scenario and operational environment.

The Swedish CAA has developed a simulation tool called STDMA/VDL Mode 4 Performance Simulator (SPS), and Eurocontrol has modified it to produce a version they call enhanced SPS. The purpose of this simulation tool is to model the VDL Mode 4 data link network management approach in order to evaluate its performance under a variety of conditions. This model has been modified further by APL to include a signal level calculation (described above), the VDL Mode 4 receiver performance model, and the necessary outputs for this evaluation.

APL has developed a UAT simulation model for use in the TLAT evaluation which is appropriate to provide a simulation of UAT that is analogous to the simulations provided for the other two link candidates.

Further information on the receiver/waveform models and simulation tools may be found in Appendices I and J, respectively.

4.2 Trials and Simulations (including Validation)

During the course of this link assessment, there were a number of flight trials of test equipment for all three candidate data links. These trials provided data used by the TLAT to support model development and validation. The trials were conducted at a number of locations, including (1) Operational and Technical Evaluations of ADS-B in the Ohio River Valley (1090 MHz Extended Squitter and UAT); (2) VDL Mode 4 testing at the FAATC; (3) LAX and Frankfurt Extended Squitter interference tests; and (4) UAT and VDL Mode 4 trials conducted in Europe. These trials were conducted under the auspices of the SF21 effort, the FAA, Eurocontrol, DFS, and other organizations. Additional data for all three link candidates has also come from laboratory bench testing conducted by APL to characterize radio equipment performance and calibrate the equipment for field testing.

These data have served a number of purposes: as reasonableness checks on the expected nominal performance of the links; as indicators of the magnitude of operational effects, such as antenna gains; as a calibration of the simulated 1090 MHz interference environment; and as information which characterizes receiver performance in the presence of noise and interference.

Since validation of simulation results in future environments is not possible, other means of verification of the reasonableness of the results are required. System characteristics represented in these simulations should agree with actual measurements on components of the proposed design, e.g., bench measurements on prototype equipment and calibrated flight test data should be compared with the modeled link budget and receiver/decoder capabilities. Similarly, flights monitoring interference levels associated with current SSR and TCAS, coupled with a suitable interference model, support estimates of how these conditions may change in future scenarios. Credibility of any simulation results for future scenarios also requires that they be able to model current conditions and provide results that appropriately agree with measurements made under these conditions. Appendix K provides further information on simulation validation performed by the TLAT.

In addition to the large-scale simulation models used to assess link performance in a future environment, there are a number of simulation tools, results from which have been made available to the TLAT. These existing tools have also been used as cross-checks for the final detailed simulations and models.

Mitre has used one or more modeling tools for each link candidate for looking at issues concerning link performance, top/bottom antenna, multipath, receiver/decoder, and signal variations. Mitre has also used an analysis tool which draws upon an external traffic distribution definition and receiver model developed from the Mitre RF model to estimate the probability of reception in face of co-channel interference, as another cross check on the large-scale simulation models. MIT Lincoln Laboratory used an internally-developed simulation for comparisons with TLAT 1090 MHz bench test results for ADS-B receivers employing enhanced decoding. Lincoln also used another analysis tool to make predictions of track acquisition in a two-aircraft encounter scenario. The Mitre and Lincoln tools have served to support a number of the analyses presented in Appendices K and M.

4.3 Analytical Assessments

The TLAT identified a number of issues that were not amenable to evaluation through the use of the large-scale simulations. This was generally due to the complexity of a data link candidate and the limitations of the corresponding large-scale simulation. Therefore, these issues were dealt with through analytical assessments, in which it was attempted to evaluate, quantitatively if possible, the particular issue or problem in question, and its effect on link performance. Each of these issues will be enumerated and discussed in turn.

TIS-B: The TLAT views TIS-B as an incremental system, i.e., it is assumed that only information on detected aircraft which are not ADS-B equipped will be broadcast by the TIS-B system on the ADS-B data link. An evaluation of the total ADS-B system load which would result from partial ADS-B equipage plus the remaining aircraft information transmitted as TIS-B information (also on the ADS-B link) was done. It was decided that the worst case load on the ADS-B data link would occur with 100% ADS-B equipage. Therefore, the future scenarios have been evaluated with 100% ADS-B equipage, and, since TIS-B is being treated as a system which supports the transition to ADS-B, TIS-B traffic has not been modeled in the full scale simulations of the high density future traffic scenarios. Support of TIS-B uplinks from a ground infrastructure perspective is addressed in the candidate link descriptions.

FIS-B: FIS-B is viewed as additional message traffic on the ADS-B data link. Furthermore, it was only applied to the future LA Basin scenario, since Eurocontrol has not yet decided whether FIS-B functionality will be provided in Core Europe through an ADS-B link.

For this assessment, FIS-B is being treated somewhat differently for each of the link candidates. For UAT, the system expert has specified that FIS-B information will be transmitted by the ground stations during the part of each UAT epoch reserved for ground station transmissions. Therefore, FIS-B messages will not interfere with UAT airborne ADS-B broadcasts. For the 1090 MHz Extended Squitter, for evaluation purposes a network of ground stations has been established, a hexagonal grid of side 60 nmi. Each of these ground stations transmits ten Extended Squitter messages per second, to simulate a representative load for FIS-B. These messages serve as interference for the ADS-B messages. For VDL Mode 4, the treatment is similar to that for UAT. A portion of the VDL Mode 4 frame is allocated as being reserved for ground station transmissions of FIS-B on one of the GSCs. Several studies were done to determine that the appropriate number of slots to reserve for ground station transmissions of FIS-B is four per second. Thus, four out of each second’s 75 slots on one VDL Mode 4 GSC are unavailable for transmission by the aircraft. In addition, for both LA and Core Europe, four slots per second have been reserved in the system design on the other GSC for ground station transmissions of Directory of Services and, e.g., transmissions of GNSS augmentations.

Channel Management of VDL Mode 4: An alternative channel management proposal to that initially specified by the TLAT VDL Mode 4 system experts has also been assessed. This proposal makes use of four channels, with only two required for transmission in any single region of airspace. Two of these channels are managed in a shared manner that depends on the location of the aircraft. The key channel management feature is to create a set of disjoint regions ("tiles") which allow for channel reuse. The tiles are organized in a hexagonal “beehive” pattern. This technique is used, for example, in cellular communications systems. Users who are far enough away from each other in different tiles can use the same frequency band for communications. In this ADS-B channel management approach, this approach is used for the sharing of slots within frequency channels. The ground directs the use of slots on these two channels, so that there is no autonomy of slot selection by individuals. Results of the analysis of this channel management scheme are presented in Appendix M.1.

VDL Mode 4 Two-Slot Messages: The transmission sequence for aircraft with Classes A2 and A3 VDL Mode 4 ADS-B equipment calls for a single two-slot message to be transmitted on one of the GSCs, in order to accommodate the requirements for TCP transmissions. The simulation model does not include a two-slot message, however, so the simulations employed indirect techniques to evaluate the impact of two-slot messages. Appendix M.2 summarizes an analysis of the effect on slot selection of two-slot messages.

Transitions Involving VDL Mode 4 Regional Signaling Channels: Since the simulation model for VDL Mode 4 cannot handle a change in broadcast rate on a channel when moving from one region of airspace to another, as is required by the VDL Mode 4 channel management plan, an analysis of this effect was undertaken. The results appear in Appendix M.3.

ADS-B Availability in Areas of Non-Radar Coverage: An analysis of the potential requirements for the use of ADS-B for separation assurance in areas of non-radar coverage is presented in Appendix M.4, with a particular configuration of avionics for the 1090 MHz Extended Squitter used as an exemplary point of evaluation.

Projections of 1090 MHz Extended Squitter Performance under Current Conditions in the LA Basin: An analysis prepared by MIT Lincoln Laboratory is presented in Appendix M.5.

Multipath Effects: Several potential effects of multipath are examined in Appendix M.6.

5 Technical Assessment

5.1 Findings

The TLAT developed findings based on the terms of reference (Appendix A) and agreed link evaluation criteria (Section 3). Section 5.1.1 presents findings related to state vector and intent information update periods at specified ranges for applications selected by RTCA's Free Flight Select Committee and Eurocontrol's ADS Programme Steering Group. Section 5.1.2 presents other findings.

All findings in this section have been unanimously agreed upon by the members of the TLAT.

5.1.1 Application Performance Results

The TLAT used both simulation results and analysis (presented in Appendices K and M) to determine the ability of the candidate links to meet the performance requirements associated with each application as specified in Section 3. The following tables depict the results for each of the three traffic scenarios discussed in Section 4.

The results are presented using the following terms:

- Supported means that the performance requirements for the application were met.
- Inconclusive means that the uncertainties associated with the simulation results were too great to permit assessment.
- Not supported means that the candidate link does not meet one or more performance requirement for the application for the specified range.
- Not addressed means that the TLAT did not have time to address this issue. Not addressed does not infer that the requirement cannot be met.
- Not applicable means that the scenario does not include the application.

Results obtained exclusively through analysis are designated as such. The following acronyms are used in the tables:

SV: State Vector

TCP: Trajectory Change Point

RSC: Regional Signalling Channel

CAP: Controller Access Parameters

A-SMGCS: Advanced-Surface Movement Guidance and Control System

ATS: Air Traffic Services

a/g: air-to-ground

TMA: Terminal Maneuvering Area

Core Europe 2015 Scenario

	1090 Extended Squitter	UAT	VDL Mode 4
SF21 Performance Criteria[1]			
Aid to Visual Acquisition (SV Update Rates to 10 nm)	Supported (by analysis)	Supported (by analysis)	Not supported except in Approach and Climb -out areas[2] (by analysis)
Conflict and Collision Avoidance (SV Update Rates to 20 nm)	Supported	Supported	For ranges above 3nm, supported within RSC and supported outside RSC when below 10000ft
Separation Assurance and Sequencing (SV and 1 TCP Update Rates to 40 nm)	Inconclusive	Supported	SV Updates are supported; Proposed TCP scheme not evaluated
Flight path deconfliction planning (SV and 2 TCP Update Rates to 90 nm)	Not supported	Requirement is met only up to 70 nm	Inconclusive
Airport Surface	Not addressed	Not addressed	Not addressed
Simultaneous approaches (SV Update Rates based upon physical runway separation)	Supported (by analysis)	Supported (by analysis)	3sec SV update req. met (by analysis)

[1] Performance Requirements are defined in Table 3.4 of the RTCA ADS-B MASPS DO-242 (Ref. 3).
[2] Requires an LSC (Local Signalling Channel) in the area.

Core Europe 2015 Scenario--continued

	1090 Extended Squitter	UAT	VDL Mode 4
Additional Eurocontrol Criteria[3]			
ATS Surveillance a/g			
TMA (SV and 4 TCP Update Rates to 60 nm)	Met with a 6-sector antenna	Likely to be met (by analysis)	Not supported with one Ground Station[4]
En-Route (SV and 4 TCP Update Rates to 150 nm)	Met up to 100 nm with 6-sector antenna[5]	Not addressed	SV Update Requirement met up to 70 nm with one omnidirectional antenna inside the RSC[6]. TCP update method provided in Appendix E but not evaluated
ATS Enhanced Surveillance a/g	Not addressed for the transmission of CAP information[7]	All parameters were addressed	Not addressed for the transmission of CAP and TCP information[8]
TMA (SV and 4 TCP Update Rates to 60 nm)	Met with a 6-sector antenna	Likely to be met (by analysis)	Not supported with one Ground Station[6]
En-Route (SV and 4 TCP Update Rates to 150 nm)	Met up to 100 nm[5]	Not addressed	SV Update Requirement met up to 70 nm with one omnidirectional antenna inside the RSC[6].
A-SMGCS			
Taxi (0-5 nm)	Not addressed	Not addressed	Not addressed
Approach (5-10 nm)	Not addressed	Not addressed	Not addressed
Autonomous air to air operations – long range (SV and 4 TCP to 150 nm)	Not supported	Not supported	Not supported

[3] Requirements proposed in the Eurocontrol document [Ref. 6].
[4] May be supported with appropriate ground infrastructure (not evaluated by the TLAT). See Appendix E.
[5] The full 150 nm requirement is expected to be met with a more complex ground antenna.
[6] May be supported with appropriate ground infrastructure (not evaluated by the TLAT). See Appendix E.
[7] Appendix F proposes the use of the Mode S datalink for the transmission of CAP information in high density airspace.
[8] Appendix E proposes the use of the VDL-4 datalink for the transmission of CAP and TCP information in high density airspace.

Los Angeles Basin 2020 Scenario

	1090 Extended Squitter	**UAT**	**VDL Mode 4**
SF21 Performance Criteria[9]			
Aid to visual Acquisition (SV Update Rates to 10 nm)	Supported (by analysis)	Supported (by analysis)	Not supported except in Approach and Climbout areas[10] (by analysis)
Conflict and Collision Avoidance (SV Update Rates to 20 nm)	Supported	Supported	Supported beyond 3nm
Separation Assurance and Sequencing (SV and 1 TCP Update Rates to 40 nm)	Unlikely to be met[11]	Supported	SV Updates are supported; Proposed TCP scheme not evaluated
Flight path de-confliction planning (SV and 2 TCP Update Rates to 90 nm)	Not supported	Supported	Inconclusive
Airport Surface	Not addressed	Not addressed	Not addressed
Simultaneous approaches (SV Update Rates based upon physical runway separation)	Supported (by analysis)	Supported (by analysis)	3 sec SV update requirement met (by analysis)

[9] Performance Requirements are defined in Table 3.4 of the RTCA ADS-B MASPS, DO-242.
[10] Requires an LSC (Local Signalling Channel) in the area.
[11] Simulations produced differing fruit environments. The requirements of the application were not met in the most likely of these fruit environments.

Los Angeles Basin 2020 Scenario - continued

	1090 Extended Squitter	UAT	VDL Mode 4
Additional Eurocontrol Criteria[12]			
ATS Surveillance a/g			
TMA (SV and 4 TCP Update Rates to 60 nm)	Not addressed	Likely to be met (by analysis)	Not supported with one Ground Station[13] (by analysis)
En-Route (SV and 4 TCP Update Rates to 150 nm)	Not addressed	Not addressed	At least as good as Core Europe 2015 because of the higher transmission rates used (by analysis)
ATS Enhanced Surveillance a/g			
TMA (SV and 4 TCP Update Rates to 60 nm)	Not addressed	Likely to be met (by analysis)	Not supported with one Ground Station[13] (by analysis)
En-Route (SV and 4 TCP Update Rates to 150 nm)	Not addressed	Not addressed	At least as good as Core Europe 2015 because of the higher transmission rates used (by analysis)
A-SMGCS			
Taxi (0-5 nm)	Not Addressed	Not addressed	Not Addressed
Approach (5-10 nm)	Not Addressed	Not addressed	Not Addressed
Autonomous air to air operations – long range (SV and 4 TCP Update Rates to 150 nm)	Not supported	Not supported	Not supported

[12] Requirements proposed in the Eurocontrol document [Ref. 6].
[13] May be supported with appropriate ground infrastructure (not evaluated by the TLAT). See Appendix E.

Low Density Scenario

	1090 Extended Squitter	UAT	VDL Mode 4
SF21 Performance Criteria[14]			
Aid to visual Acquisition (SV Update Rates to 10 nm)	Supported (by analysis)	Supported (by analysis)	Not supported (by analysis)
Conflict and Collision Avoidance (SV Update Rates to 20 nm)	Supported (by analysis)	Supported	Not supported (all a/c in scenario are en route and above 10000ft)[15]
Separation Assurance and Sequencing (SV and 1 TCP Update Rates to 40 nm)	Likely to be supported (by analysis)	Supported	SV updates supported in 20 to 40 nm and TMAs; TCP change is likely to be met (by analysis); Acquisition was not evaluated;
Flight path de-confliction planning (SV and 2 TCP Update Rates to 90 nm)	Likely to be supported (by analysis)	Supported	SV updates supported TCP change is likely to be met (by analysis); Acquisition was not evaluated;
Airport Surface	Not applicable	Not applicable	Not applicable
Simultaneous approaches (SV Update Rates based upon physical runway separation)	Not applicable	Not applicable	Not applicable
Additional Eurocontrol Criteria[16]			
ATS Surveillance a/g			
TMA (SV and 4 TCP Update Rates to 60 nm)	Not applicable	Not applicable	Not applicable
En-Route (SV and 4 TCP Update Rates to 150 nm)	Not addressed	Not addressed	Not addressed
ATS Enhanced Surveillance a/g	Not applicable	Not applicable	Not applicable
TMA (SV and 4 TCP Update Rates to 60 nm)			
En-Route (SV and 4 TCP Update Rates to 150 nm)			
A-SMGCS	Not applicable	Not applicable	Not applicable
Taxi (0-5 nm)			
Approach (5-10 nm)			
Autonomous air to air operations – long range (SV and 4 TCP to 150 nm)	Unlikely to be met to 150 nm; may be possible to <120 (by analysis)	Supported	SV updates supported TCP change is likely to be met (by analysis); Acquisition was not addressed

[14] Performance Requirements are defined in Table 3.4 of the RTCA ADS-B MASPS DO-242.
[15] VDL-4 could support the requirement in TMAs with ground stations (see Appendix E).
[16] Requirements proposed in the Eurocontrol document [Ref. 6].

The TLAT agreed to the following observations concerning the sensitivity of the values noted in the tables above to particular simulation and analytical assumptions.

a) The VDL Mode 4 system is highly configurable and may be optimised in a number of ways in a particular air traffic environment.

b) VDL Mode 4 performance improvements may be achieved through the use of sectorised ground antennas.

c) The VDL Mode 4 MOPS requires (protocol level) co-channel interference (CCI) performance (10 dB) at least 2 dB better than the value stated in Appendix E. VDL Mode 4 simulations assumed a 10 dB CCI threshold.

d) Trajectory change point transmission rates for UAT and VDL Mode 4 are subject to further optimisation.

e) The 1090 MHz Extended Squitter simulations suggest that a breakpoint in 20 to 40 nm performance occurs within the range of fruit environments examined.

f) A 1090 MHz Extended Squitter ADS-B receiver as specified in Draft DO-260 will exhibit significantly lower performance than that summarised above for the scenarios considered by the TLAT. Receivers conforming to DO-260A (which is the case assumed in Appendix F) are expected to perform as indicated in the tables.

The TLAT agreed to the following observations concerning the capacity (relating to the number of ADS-B system participants) of the candidate links:

a) In the high density traffic scenarios considered by the TLAT, there is no excess ADS-B capacity for any of the links as defined in their System Descriptions.

b) None of the three links meets all performance requirements in all three traffic scenarios. However, UAT was assessed as meeting all evaluated TLAT range and update rate requirements in the case of the low density scenario.

c) All three links exhibit a graceful degradation of performance with regard to the parameters listed in the tables above in the presence of interference.

5.1.2 Further Findings

For **TIS-B**, the TLAT has considered the capability of the candidate links to support the service, but in terms of simulations it was not taken into account as the 100% ADS-B equipage scenario is considered more loaded than a mixed ADS-B TIS-B scenario. All link candidates have the capability to uplink TIS-B information.

FIS-B was evaluated by simulation using the future LA Basin scenario (2020). The following apply to FIS-B capacity for each link relative to the TLAT evaluation rate:

a) UAT was the only link shown to have FIS uplink capacity substantially greater than the TLAT evaluation rate. The total capacity of the protected uplink slots had over 80 times the TLAT evaluation rate.

b) VDL Mode 4 met the TLAT evaluation rate.

c) 1090 MHz Extended Squitter was shown to deliver about one third of the TLAT evaluation rate at the maximum range.

There are several items to consider when assessing the **time until implementation**—availability of standards, availability of spectrum, and complexity. Regarding standards:

a) **1090 MHz Extended Squitter**: The system described in Appendix F contains features not standardised in the current MOPS (RTCA DO-260/ED-102). RTCA DO-260A currently in progress is expected to include these features. SARPs for Extended Squitter are in place; SARPs harmonised to DO-260A await completion of DO-260A. Complementary AEEC characteristics are expected to be completed by the end of 2001. The TLAT is unaware of any standards activity for 1090 MHz ES ground stations.

b) **UAT**: RTCA MOPS activity has been initiated and is scheduled to be completed by February 2002. SARPs and AEEC characteristics have not been initiated. The FAA intends to request initiation of SARPs development. The TLAT is unaware of any standards activity for UAT ground stations.

c) **VDL Mode 4**: SARPs have been approved and will be published by November 2001. EUROCAE MOPS are scheduled to be approved and published by mid 2001. European Telecommunications Standardisation Institute (ETSI) standards for radio station approval for ground stations are expected mid 2001. Additional ETSI work is ongoing. AEEC activity has not been initiated as yet.

Regarding availability of spectrum:

a) **1090 MHz Extended Squitter**: International spectrum allocation of the required 3 MHz channel exists. No further action is required.

b) **UAT**: Operating frequencies (supporting the required 3 MHz channel) must be identified. This will be done during the SARPs development process. International coordination of the UAT frequency is expected to take until 2006. After identification of a UAT frequency, DME channel(s) will need to be cleared.

c) Resolution of interference issues concerning **UAT** and **JTIDS/MIDS**, an important military tactical datalink, is critical to the deployment of UAT. The TLAT's evaluation of UAT has not taken into account the effects of JTIDS/MIDS systems. The UAT MOPS activity is considering this issue.

d) **VDL Mode 4**: VDL Mode 4 requires seven 25 KHz channels to operate in the high density scenarios evaluated by TLAT. The seven channels include: two Global Signalling Channels, two Regional Signalling Channels, two Local Signalling Channels, and one ground channel.

e) ICAO working groups are tasked to identify Global Signalling Channels. **VDL Mode** 4 operation in the VHF navigation band may require International Telecommunications Union coordination. The international co-ordination of the VDL Mode 4 Global Signalling Channels is expected to take until 2003.

The last aspect for time to implement relates to risk and complexity.

a) Implementation of ADS-B on any of the links—for performance consistent with the System Descriptions—will require new equipment installations.

b) A limited 1090 Mhz Extended Squitter capability (supporting Aid to Visual Acquisition and Conflict Detection and Collision Avoidance applications) is available as an option now with new TCAS and transponder installations (installations since 1999), and could offer some near-term benefits.

c) Long-range, SARPs- and MOPS-compliant receivers are expected to be available within one year from the completion of DO-260A (receiver availability is estimated by 2003). These estimates apply to applications that require a maximum of 2 Trajectory Change Points (TCPs). The development and certification of avionics to support more than two TCPs applications may take longer.

d) Standards-compliant VDL Mode 4 avionics are expected to be available in the near future. The current standards address equipment of two receivers (while Appendix E proposes a four-receiver configuration).

e) UAT, as currently defined, has the simplest technical concept of the candidates. This simplicity suggests that the necessary validation testing and standards development may be accomplished relatively expeditiously. Presuming that JTIDS/MIDS interference issue is resolved, UAT avionics complying with Appendix D are expected to be available in 2003.

f) The TLAT is aware that Russia has published an order that determines October 1, 2005, as the date to start using ADS-B for air traffic monitoring in Russian airspace. Russia has indicated to ICAO that it plans to implement VDL Mode 4-based ADS-B.

The TLAT agreed to the following additional observation concerning the ability of the candidate links to be integrated with and/or coexist with existing systems:

- Any operational frequency chosen for UAT will require coexistence with the JTIDS/MIDS military tactical data link. The TLAT's UAT results presume resolution of this important issue in a manner that does not add adverse interference to that used in the TLAT simulations.

The TLAT agreed to the following observation concerning the abilities of the candidate links to mitigate potentially catastrophic issues raised in the FAA's ADS-B Operational Safety Assessment [Ref. 5]:

- It is important for the ADS-B system to have a means for independent air-to-air range validation to reduce the risk of spoofing. Both UAT and VDL Mode 4 offer this capability by passive range monitoring. The 1090 MHz Extended Squitter ADS-B system as currently defined in DO-260 or Appendix F has no provision for air-to-air passive range monitoring (proposals to add this function to the system are under consideration for Draft DO-260A). Active air-to-air range monitoring can be employed by TCAS-equipped aircraft; however, the range of this active range monitoring is limited.

The TLAT agreed to the following observations concerning the expandability of the candidate links:

a) Future applications may require air-to-air two way data link. The combination of long range operation and the ability to provide two-way data link may make VDL Mode 4 attractive to support these future applications. UAT as currently defined does not support two way data link. TCAS-based installations could be modified to provide a two-way air-to-air data link capability for short- to medium-range applications.

b) All three links can be upgraded to support the broadcast of additional (to what is specified in RTCA DO-242) information, although VDL Mode 4 and UAT have more flexibility in this respect than does the 1090 MHz Extended Squitter.

c) In the high density scenarios considered, none of the three links appear to have excess air-to-air and air/ground capacity. The UAT System Description in Appendix D provides a uplink mechanism that is independent of the number of aircraft using the channel. In the case of VDL Mode 4, there is also a protected uplink mechanism; however, the capacity is less than that of UAT.

d) VDL Mode 4 has the capability to provide Global Navigation Satellite System (GNSS) augmentation services, and the channel loading from this application has been considered in the TLAT high density simulations. Although the ICAO GNSS panel is not currently considering VDL Mode 4 as a means to uplink GNSS augmentation, regional implementation of this capability is planned.

The TLAT considered general multi-link issues; this work is summarised in Appendix L. Multi-link discussions are ongoing within the FAA and Eurocontrol.

5.2 Areas for Potential Further Study

5.2.1 Multipath

Appendix M.6 provides an analysis of multipath effects for air to air, air to ground, and airport surface operations using L-Band and VHF datalinks. This analysis shows that the potential of multipath for degrading L-Band long range air to air decoder performance. The TLAT simulations did not include multipath effects. Measurements are available from several sources, see Appendix N.1. The complexity of the RF environment particularly for airport surface operations suggests that further investigations are necessary.

5.2.2 Propagation in VDL Mode 4

The modelling of overlapping interfering signals (due to propagation delays) used in the TLAT VDL Mode 4 simulations was based on theoretical analysis. This model should be further refined and validated. Appendix N.2 indicates that the effect of overlaps due to propagation delay in the TLAT VDL Mode 4 simulation results was far smaller than other uncertainties.

5.2.3 Range Limit of Core Europe Scenario

The Core Europe 2015 scenario used by the TLAT was specifically designed to measure performance in the scenario center (Brussels) and had a range of 300 nm. Appendix N.3 indicates that this scenario would have to be extended in order to measure performance in areas lying in the periphery and/or adjacent areas.

5.2.4 Multi-link

The TLAT considered general multi-link issues, this work is summarized in Appendix L. Multi-link discussions are ongoing within the FAA and Eurocontrol.

5.2.5 Co-site interference

Co-site interference is highly implementation dependent and will vary with each aircraft depending on its type, antenna location, and installation quality. The TLAT has not been able to assess the potential co-site issues relating to VDL Mode 4. Appendix N.5 indicates that VDL Mode 4 frequency planning criteria are being considered by the ICAO AMCP Working B. Co-site interference should therefore be further investigated when these criteria are in place.

5.2.6 Terrain Effects

The TLAT 1090 simulations of the Los Angeles Basin 2020 scenario considered terrain effects. The results suggest that inclusion of the terrain had a significant effect on ADS-B performance depending on the aircraft altitude distribution. Appendix N.6 indicates that terrain effects need to be considered also for VDL Mode 4 evaluations.

5.2.7 "Honeycomb" Channel Management Scheme for VDL Mode 4

Appendix E, Attachment 3 describes an alternative scheme for VDL Mode 4 channel management based on centralised ground control of channel access. Appendix N.7 provides an initial analysis of this scheme, suggesting that further investigations will be needed to establish its feasibility and benefits.

6. References

(1) RTCA, Phase One Link Evaluation Report: Status and Initial Findings, RTCA Free Flight Select Committee, Safe Flight 21 Steering Committee, Safe Flight 21 Technical/Certification Subgroup, ADS-B Link Evaluation Team, November 1999.

(2) RTCA, Joint Government/Industry Roadmap for Free Flight Operational Enhancements, August 1998, RTCA Select Committee.

(3) RTCA, Minimum Operational Performance Standards for 1090 MHz Automatic Dependent Surveillance—Broadcast (ADS-B), RTCA DO-260, September 13, 2000.

(4) RTCA, Minimum Aviation System Performance Standards for Automatic Dependent Surveillance—Broadcast (ADS-B), RTCA DO-242, January 7, 1998.

(5) Federal Aviation Administration, Automatic Dependent Surveillance Broadcast Operational Safety Assessment Report, August 13, 2000.

(6) Eurocontrol, Eurocontrol ADS Programme Proposed Criteria for ADS-B Datalink Technical Assessment, October 13, 2000.

Appendix A

Joint Safe Flight 21 (SF21) Steering Committee (SC) /
EUROCONTROL ADS Program Steering Group (PSG)
Technical Link Assessment Team

Terms of Reference

As Approved by the SF21 Steering Committee, June 2000, and
EUROCONTROL ADS PSG, September 2000, and
Amended in January 2001

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1. Produce an updated Technical Link Assessment Report evaluating the suitability of three candidate ADS-B/situational awareness[1] radio-frequency links used alone or in combination: 1090 Extended Squitter, UAT, and VDL Mode 4. This Report, to the SF21 Steering Committee (SC) and Eurocontrol ADS PSG, should be produced by the end of November, 2000.

2. Review the previously defined Eurocontrol and SF/21 DLET methodologies for the technical link evaluation process leading to a set of technology evaluation criteria and, if required, propose changes to the SF21 SC and Eurocontrol ADS PSG.

3. Expand and refine as appropriate, for SF21 Steering Committee and Eurocontrol ADS PSG approval, the set of technical link evaluation criteria to support the ADS-B link decision process, including specifically consideration of the following:
   - i) applications to be supported (as indicated by either SF21 SC or Eurocontrol) but were not considered in the Phase 1 Link Evaluation Report;
   - ii) technical requirements derived from additional applications (to be supplied by Eurocontrol);
   - iii) technical aspects of the use of multiple ADS-B/situational awareness[1] links for different aircraft types and in different airspace types, identifying any technical advantages/disadvantages and outstanding issues;
   - iv) technical implications of spectrum availability;
   - v) Interference /compatibility issues of each datalink with other systems or applications;
   - vi) any link-dependent criteria uncovered by ADS-B operational safety assessments;
   - vii) potential criteria for expandability and excess capacity.

4. Continue and complete the analysis of link performance data and link simulations (including additional bench testing and modeling as required) with respect to the link evaluation criteria, as approved by the SF21 Steering Committee and Eurocontrol ADS PSG, and the agreed air traffic and ground infrastructure scenarios. Use the link data gathered during evaluations and trials to further validate the link simulations.

5. Assess expected compliance to ADS-B MASPS, to European requirements, and to requirements for TIS-B and FIS-B, for each candidate link or combination of links using the defined scenarios. Assessment will proceed using simulation, modeling results, and field data in comparison to normalized criteria and by examination of detailed simulation outputs of each received message.

[1] situational awareness as facilitated by the availability of ADS-B, TIS-B, FIS-B, and CFIT data

6. Recommend, for SF21 Steering Committee and Eurocontrol ADS PSG approval, any additional sources of actual link performance data to be used in developing the updated Technical Link Assessment Report.
   i) Define the necessity and scope of multipath testing for the candidate links;
   ii) Develop procedures and define test configurations to measure received signal level and noise power in dBm during field measurements.

7. Participate in relevant FAA and Eurocontrol link activities by providing guidance on data gathering and by performing analysis of collected data (Examples of these activities include the 1090 ADS-B Trial being conducted by Eurocontrol, FAA and DFS in Frankfurt, and the ADS-B link simulations being conducted by Johns Hopkins University, Eurocontrol and SCAA).

8. Provide technical expertise, if requested, in support of the datalink safety assessment activities ongoing within Eurocontrol and the FAA.

9. Develop the updated Technical Link Assessment Report based upon the expanded link evaluation criteria, ADS-B operational evaluation data, link performance and simulation data, and compliance to ADS-B MASPS and European requirements.

10. Leadership

The Joint SF21 SC/ADS PSG Technical Link Assessment Team will report to both the Safe Flight 21 Steering Committee and the Eurocontrol ADS Program Steering Group.

11. Membership

Ann Tedford, FAA/ASD-100, Co-chair
Constantine Tamvaclis, Eurocontrol Experimental Centre, Co-chair

George Ligler, PMEI, Team Facilitator

Vince Nguyen, FAA/AND-500
Don Willis, FAA/ASR-100
Tom Pagano, FAA/ACT-300
Stan Jones, MITRE
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Nikos Fistas, Eurocontrol
John Gonda, DoD/USAF
Rich Weathers, DoD/JCS

Subject Matter Experts (SME):
Bill Harman, LL
Jonathan Bernays, LL
Chris Moody, MITRE
Johnny Nilsson, Swedish CAA
Christian Axelsson, Swedish CAA
Armin Schlereth, DFS

Additional members:
Additional members may be co-opted at any time at the discretion of either Co-chair.

Related Activities
Contact with Industry

The SMEs of each radio-link technology will maintain regular contact with all relevant avionics manufacturers active in the relevant technology field and airframe manufacturers.

Appendix B

RTCA Safe Flight 21 Steering Committee
EUROCONTROL ADS Programme Steering Group

Technical Link Assessment Team (TLAT) and Key Contributors

TLAT

Ann Tedford, Co-Chair	Federal Aviation Administration (FAA), Architecture and Systems Engineering
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Pieter van der Kraan	EUROCONTROL
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Appendix C

Summary Table of Selected Technical Characteristics of Link Candidates

Characteristic	1090 MHz Extended Squitter: Proposed Operational System	1090 MHz Extended Squitter: 1999 U.S. Tests	VDL Mode 4: Proposed Operational System	VDL Mode 4: 1999 U.S. Tests	UAT: Proposed Operational System	UAT: 1999 U.S. Tests
Frequency Band	1090 MHz	Same	118-137 MHz (in addition Rec. for 108-117.975 MHz)	112-118 MHz	Not Assigned	966 MHz
Bit Rate	1 Megabit/sec	Same	19200 bits/sec/channel	Same	1.041667 Megabits/sec	Same
Modulation	PPM	Same	Binary GFSK/FM	Same	Binary GFSK $\pm$312 KHz	Same
Synchroni-zation	4 pulse preamble (9 pulse processing)	Same	First 24 bits Plus burst flag	Same	First 36 bits	Same
Message Length	112 bits	Same	192 bits after synchronization	Same	246 bits, short 372 bits, long	Same
Parity	24 bits	Same	16 bits	Same	48 bits FEC and 24 bits CRC	Same
Address	24 bits	Same	3+24 bits	Same	25 bits	Same
Airborne Longitude	CPR 17 bits, even 17 bits, odd LSB ~5 meters	Same	Compressed 18-22 bits even 16-20 bits odd LSB ~1-18 meters	Same	Uncompressed 24 bits LSB = 2.3 meters	Same
PVT Segmentation?	Yes: Velocity in separate message	Same	No: PVT in one message	Same	No: PVT in one message	Same
Transmitter Power (at Antenna)	51-57 dBm, high-end 48.5-57 dBm, low-end	Same	43-44.5 dBm, high-end (ground station) 39-40.5 dBm, medium 36-37.5 dBm, low-end	44, 39.8, and 37.8 dBm	50-54 dBm, high-end 44-48 dBm, low-end	44 dBm +/- 3 dB
Receiver MTL (90%) (at Antenna)	$\leq$ -84 dBm, high end $\leq$ -72 dBm, low-end	~-79 to ~-87 dBm	$\leq$ -103 dBm at 10^{-4} BER	-80 and –90 dBm at 1% MER	$\leq$ -93 dBm	-93 dBm
Polarization	Vertical	Same	Vertical	Same	Vertical	Same
Transmission Rate for PVT	Position at 2 Hz Velocity at 2 Hz	Same	1, 2, 5, or 10 seconds (can be varied between 1-60; event-driven or by command)	PVT every 1 second	PVT every 1 second	Same
Transmission Rate for Intent/Flight Ident.	3.4 per second	0.75 per second	Each TCP once every minute. Flight Ident. Once every 5 minutes	Not transmitted	Within same Message as PVT	Flight Ident. Transmitted
Multiple Access Technique	Random messages	Same	Self-organizing TDMA (75 slots/second per channel)	Same	Slots to separate ground/air. Aircraft use random messages	Same
RF Channels	One channel	Same	2 (25KHz) Global Signaling Channels, plus up to 2 Regional and 3 Local Channels in High Density Airspace	2 Channels (Used as if Global)	One Channel	Same

Acronyms:

BER	Bit Error Rate
CPR	Compact Position Reporting (Compression)
CRC	Cyclic Redundancy Code
FEC	Forward Error Correction
GFSK	Gaussian Frequency Shift Keying
LSB	Least Significant Bit
MER	Message Error Rate
MTL	Minimum Trigger Level
PPM	Pulse Position Modulation
PVT	Position, Velocity and Time (Information for ADS-B State Vector)
RF	Radio Frequency
TCP	Trajectory Change Point
TDMA	Time Division Multiple Access

Appendix G: TLAT Link Evaluation Criteria

The TLAT criteria can be classified in two categories: criteria that access the performance of the candidate links, and criteria that are not relating to the performance but are necessary considerations for a comprehensive evaluation of the candidate links.

In terms of performance, the criteria are mainly driven by two major sources: the operational enhancements identified by the SF21 Free Flight Committee and the scenarios and applications considered by Eurocontrol.

For the first source, the TLAT used the criteria developed by SF21 Link Evaluation Team (LET). The development by LET of technical link evaluation criteria to support Safe Flight 21 applications proceeded in the following manner:

STEP 1:
The LET identified industry consensus reference documents upon which to base the link evaluation criteria. The Safe Flight 21 Steering Committee approved the use of the following two reference documents:

- Joint Government/Industry Plan for Free Flight Operational Enhancements, August 1998, RTCA Free Flight Select Committee.
- RTCA DO-242, Minimum Aviation System Performance Standards (MASPS) for ADS-B.

STEP 2:
Using these documents, the LET identified appropriate ADS-B MASPS requirements to be used as evaluation criteria for the candidate links. Attachment 1 outlines the ADS-B MASPS requirements and the originating Free Flight Operational Enhancements as identified by the LET. Attachment 2 is excerpts from the ADS-B MASPS highlighting the MASPS requirements identified in by the LET.

STEP 3:
Finally, the LET developed additional technical criteria, which are not covered by the ADS-B MASPS but are needed to support the Free Flight Operational Enhancements. Consideration of the Operational Enhancements made it clear that requirements related to the support of FIS-B services, which are not in the ADS-B MASPS, would need to be developed.

With regard to FIS-B requirements, the LET considered the draft MASPS for FIS-B under development by RTCA, as well as the FIS-B spectrum requirements discussed in RTCA DO-237. Additionally, the SF21 Steering Committee provided a prioritisation of FIS-B services (e.g., weather information) to assist the LET in its development of requirements. The LET developed a data link requirement for FIS-B on the order of 200 bits per second per ground station.

For TIS-B, the TLAT has considered the capability of the candidate links to support the service, but in terms of simulations it was not taken into account as the 100% ADS-B equipage scenario is considered more loaded than a mixed ADS-B TIS-B scenario.

In addition to the above criteria, the TLAT used in its evaluation an additional set of performance criteria, which were developed and proposed by Eurocontrol.

These criteria were developed by the ADS Concept and Requirements Task Force of the ADS Programme, in an iterative process taking into account comments by the stakeholders. These criteria represent a snapshot of the ongoing discussion in Europe in relation to the ADS-B requirements and as such were endorsed by the ADS Concept and Requirements Task Force and the ADS Programme Steering Group (PSG). The Eurocontrol criteria are detailed in Attachment 3.

In addition to performance issues, the TLAT considered the use of technical criteria to address implementation and institutional aspects as a necessary component of the evaluation. While evaluation of the candidate links using these criteria necessarily involves some subjectivity, the considerations involved are technical and therefore were deemed appropriate to the TLAT.

Appendix G, Attachment 1

LET ADS-B Link Evaluation Criteria

The LET during the development of the link evaluation criteria examined all the Free Flight Operational Enhancements with the aim of determining whether there are any resulting requirements. Where requirements were identified then the corresponding requirement in the RTCA ADS-B MASPS was used as an evaluation criterion.

Where the MASPS requirements were not applicable (e.g. for TIS/FIS) or to cover additional considerations (technical issues), the LET identified additional evaluation criteria.

The result of the LET analysis is as follows:

No link dependent requirements were identified for the following Free Flight Operational Enhancements:

- CFIT Avoidance and situational awareness

For the following Free Flight Operational Enhancements requirements were identified as in the following table:

Free Flight Operational Enhancements	Requirements
Weather and other information into the cockpit (FIS for SUA Status, Weather, Wind-Shear, NOTAMs, PIREPS)	draft RTCA SC-169 FIS-B MASPS
Improved Terminal Operations in Low Visibility Conditions	ADS-B MASPS Table 3-4:First 2 Columns, First 5 Rows, TIS Requirements under Review
Enhanced Visual Operations and Situational Awareness	ADS-B MASPS, Table 3-4:First Column, First 5 Rows, TIS Requirements under Review.
Enhanced Operations for En-Route and Oceanic Air-to-Air	ADS-B MASPS, Table 3-4: First Four Columns, First 5 Rows
Improved Surface/Approach Operations	ADS-B MASPS, Table 3-4: First and Sixth Column, First 5 Rows
Surface and Airport Vicinity Display for the Controller	ADS-B MASPS, Table 3-4: First and Sixth Columns, First 5 Rows. (Note Also Table 2-4, 2nd and 3rd columns)
Use ADS-B in Non-Radar Airspace ADS-B to Enhance Radar and Automation Performance	ADS-B MASPS, Table 3-4: First Four Columns, First 5 Rows ADS-B MASPS: Table 3-4: First 4 columns, First 5 Rows

For all Operational Enhancements, where requirements are identified, the integrity, continuity, and availability Requirements of ADS-B MASPS, Section 3.3.6 apply.

In addition to the Free Flight Enhancements the LET decided to consider and evaluate how the candidate links would support the Simultaneous Approach Scenario in the ADS-B MASPS (10 nmi)

Appendix G, Attachment 2

Excerpt of ADS-B MASPS: Summary of Identified Requirements

(MASPS Tables 2-4, 3-4, and Excerpts from MASPS Section 3.3.6)

Table 2-4a. Summary of ATS Provider Surveillance and Conflict Management Current Capabilities for Sample Scenarios [a]

	Operational Capability			
Information	En Route	Terminal	Airport Surface	Parallel Runway Conform Mon.
Initial Acquisition of A/V Call Sign and A/V Category	Within 24 sec.	within 10 sec.	within 10 sec.	n/a
Altitude Resolution (ft)	25	25	25	25
Horizontal Position Error	388 m @ 200 nmi 116 m @ 60 nmi 35 m @ 18 nmi	116 m @ 60 nmi 35 m @ 18 nmi	3 m. rms, 9 m. bias [15],[6], [11]	9 m.
Received Update Period [b]	12 sec. [10]	5 sec. [6]	1 sec.	1 sec.
Update Success Rate	98%	98%	98% [6]	98%
Operational Domain Radius (nmi)	200	60	5	10
Operational Traffic Densities [c] (# A/V)	1250 [6]	750 [6]	100 in motion; 150 fixed	50 dual; 75 triple; w/o filter: 150
Service Availability [d] (%)	99.999 [10] 99.9 (low alt)	99.999 [10] 99.9 (low alt)	99.999 [10]	99.9

Table 2-4b. Additional and Refined Capabilities Appropriate for ADS-B Supported Sample Scenarios [a]

	Operational Capability			
Information	En Route	Terminal	Airport Surface	Parallel Runway Conform Mon.
Altitude Rate Error [e] (1σ)	1 fps	1 fps	1 fps	1 fps
Horizontal Velocity Error (1σ)	5 m/s	0.6 m/s	0.3 m/s	0.3 m/s
Geometric Altitude	Yes	yes	Yes	Yes
Turn Indication	Yes	yes	TBD	Yes

n/a (not applicable) = the requirement is not stressful and would not be higher than any other requirement, i.e., does not drive the design.

tbd = To be determined.

Notes(Table 2-4):

a) *References are provided where applicable. Else, best judgment was used to obtain performance data.*

b) *Received update period is the period between received state vector updates. A/V Call Sign and A/V Category can be received at a lower rate.*

c) *One or multiple ground receivers may be used in the operational domain to ensure acceptable performance for the intended traffic load. The numbers in the table indicate the number of aircraft expected to participate in or affect a given operation. (Refer to Table 3.3-1 for requirements which are based on operational traffic densities derived from the Los Angeles basin model)*

d) *Service availability includes any other systems providing additional sources of surveillance information.*

e) *Altitude accuracy: Some aircraft currently have only 100 ft resolution capability.*

Table 3.4 ADS-B Report Accuracy, Update Period, and Acquisition Range Requirements

	Aid to Visual Acquisition	Conflict Avoidance and Collision Avoidance	Separation Assurance and Sequencing	Flight Path Deconfliction Planning	Simul-taneous Approach	Airport Surface (note 5)
State Vector Acquisition Range	10 nmi	20 nmi	40 nmi	90 nmi (note 3); (120 nmi desired)	10 nmi	5 nmi
Mode-status Acquisition Range (note 8)	10 nmi	20 nmi	40 nmi	90 nmi (note 3) (120 nmi desired)	10 nmi	5 nmi
On Condition Acquisition Range (note 8)	n/a	n/a	n/a	90 nmi (note 3) (120 nmi desired)	10 nmi	TBD
Nominal Update Period (95th percentile) (note 6) (note 7)	<= 3 s (3 nmi) <= 5 s (10 nmi)	<= 3 s (3 nmi) (1 s desired, note 2) <= 7 s (20 nmi)	<= 7 s (20 nmi) <= 12 s (40 nmi)	<= 12 s	<= 1.5 s (1000 ft runway separation) <= 3 s (1 s desired) (2500 ft runway separation)	<= 1.5 s
99th Percentile State Vector Report Received Update Period (Coast Interval) (Note 7, 8)	<= 6s (3 nmi) <= 10 s (10 nmi)	<= 6 s (3 nmi) <= 14 s (20 nmi)	<= 14 s (20 nmi) <= 24 s (40 nmi)	<= 24 s	<= 3s (1000 ft runway separation) (1s desired, note 2) <= 7s (2500 ft runway separation)	<= 3 s
Permitted Total State Vector Errors Required To Support Application (1 sigma, 1D)	σ_{hp} = 200 m σ_{hv} = n/a σ_{vp} = 32 ft σ_{vv} = 1 fps	σ_{hp} = 20 / 50 m (note 1) σ_{hv} = 0.6/ 0.75 m/s (note 1) σ_{vp} = 32 ft σ_{vv} = 1 fps	σ_{hp} = = 20 / 50 m (note 1) σ_{hv} = 0.3/ 0.75 m/s (note 1) σ_{vp} = 32 ft σ_{vv} = 1 fps	σ_{hp} = 200 m σ_{hv} = 5 m/s σ_{vp} = 32 ft σ_{vv} = 1 fps	σ_{hp} = 20 m σ_{hv} = 0.3 m/s σ_{vp} = 32 ft σ_{vv} = 1 fps	σ_{hp} = 2.5 m (note 9) σ_{hv} = 0.3 m/s σ_{vp} = n/a σ_{vv} = n/a
State Vector Errors Budgeted for ADS-B (1 sigma, 1D) (Note 10)	σ_{hp} = 20 m σ_{hv} = 0.25 m/s σ_{vp} = 30 ft σ_{vv} = 1 fps (Note 11)					σ_{hp} = 2.5 m (note 9) σ_{hv} = 0.25 m/s σ_{vp} = n/a σ_{vv} = n/a

Definitions:

σ_{hp}: standard deviation of horizontal position error.

σ_{hv}: standard deviation of horizontal velocity error.

σ_{vp}: standard deviation of vertical position error.

σ_{VV}: standard deviation of vertical velocity error.

Notes:

1) The lower number represents the desired accuracy for best operational performance and maximum advantage of ADS-B. The higher number, representative of GPS standard positioning service, represents an acceptable level of ADS-B performance, when combined with barometric altimetery.

2) The analysis in Appendix J indicates that a 3-second report received update period for the full state vector will yield improvements in both safety and alert rate relative to TCAS II, which does not measure velocity. Further improvement in these measures can be achieved by providing a one-second report received update rate Further definition of ADS-B based separation and conflict avoidance system(s) may result in refinements to the values in the Table.

3) The 90 nmi range requirement applies in the forward direction. The required range aft is 30 nmi (40 nmi desired). The required range 90 degrees to port and starboard is 45 nmi (60 nmi desired) (see Appendix H).

4) n/a = not applicable; TBD = To be defined

5) Requirements apply to both aircraft and vehicles.

6) Supporting analyses for update period and update probability are provided in Appendices J and L.

7) Acceptable combinations of report update period (T) and update probability (P) are given by the formula $(1-P)^{TC/T} <= 0.01$ where TC is the 99th percentile report update period given in the table. For example, for conflict avoidance, TC = 6 sec.; a report update period of T=3 would require P=0.9 or greater. As a second example, for conflict avoidance, if P=0.5, then T must be 0.9 seconds or less.

8) The delay for MS or OC report updates after a MS or OC state change should be no more than the coast interval associated with the state vector report (with 95% confidence).

9) The position accuracy requirement for aircraft on the airport surface is stated with respect to the certified navigation center of the aircraft.

10) This row represents the allowable contribution to total state vector error from ADS-B.

11) The horizontal velocity error requirements to aircraft speeds of up to 600 knots. Accuracies required for velocities above 600 knots are TBD.

12) Specific system parameter requirements in Table 3.3-3 can be waived provided that the system designer shows that the application design goals stated in Appendix J or equivalent system level performance can be achieved.

13) Update periods for the SV have been emphasized in determining link related performance requirements in this table. Lower rates of MS and OC are under development. These reports should be made available to support the operational capabilities using considerations equivalent to the SV. The requirement should be optimized to ensure that the refresh/update of reports is appropriate for the equipment classes and the operations being supported. Refer to the analysis presented in Appendix L for further details.\

3.3.6 ADS-B System Quality of Service

3.3.6.2 Failure Mode and Availability Considerations

Navigation and radar surveillance in the horizontal dimensions are independent; this independence is beneficial under certain failure modes. Today, an aircraft with failed navigation capability may get failure mode recovery vectors from ATS based on SSR/PSR tracks. Today, an aircraft with a failed transponder may still report navigation based position information to ATS for safe separation from other traffic even if no PSR is available. On the other hand, a navigation capability failure in an ADS-B only surveillance environment results in both the aircraft and ATS experiencing uncertainty about the aircraft's location. The operational impact of such a failure depends upon the nature of the failure: i.e., a single unit failure, or an area wide outage. Additional factors include the duration of the failure, the traffic density at the time of the failure, and the overall navigation and surveillance architecture. Detailed treatment of these issues should consider the failure mode recovery process in the context of the service outage duration and the total CNS environment. Figure 3.3-2 suggests how such a failure mode recovery process depends upon the total ATS architecture. Different states may implement different ATS architectures.

It is anticipated that ADS-B will be used as a supplemental means of surveillance for some ATS-based airspace operations during a transition period leading to full ADS-B equipage. When used as a supplemental means of surveillance, ADS-B adds availability within a larger surveillance system. Primary means of surveillance is defined as a preferred means (when other means are available) of obtaining surveillance data for aircraft separation and avoidance of obstacles. Use of ADS-B as a sole means of surveillance presumes that aircraft can engage in operations with no other means of surveillance. If ADS-B were to be used as a sole means of surveillance, availability would be calculated using only ADS-B, aircraft sources, and applications. ADS-B is not expected to be used as a sole means of ATS surveillance for the near future in US domestic airspace.

Where the ADS-B System is used as a supplemental means of surveillance, the ADS-B system is expected to be available with a probability of at least 0.95 for all operations, independent of the availability of appropriate inputs to the ADS-B system. Where the ADS-B System is used as a primary means of surveillance, the system is expected to be available with a probability of at least 0.999 for all air-air operations.

If an ADS-B system is used as a primary means of surveillance, then a supplemental surveillance system, independent of the navigation system, is expected to be available. The overall surveillance system will need to satisfy fail-safe operation of navigation and surveillance, i.e., a failure of the navigation system will not result in a failure of the surveillance function. This will enable ATS to provide an independent means of guidance to aircraft losing all navigation capability. The overall requirement for the surveillance system is adequate availability of the surveillance function, independent of navigation system availability. Where this requirement cannot be satisfied in a system intended for primary means of surveillance, the avionics and support infrastructure should be designed such that the simultaneous loss of both navigation and surveillance is extremely improbable. The expected availability of the total surveillance system is at least 0.99999, independent of navigation system availability.

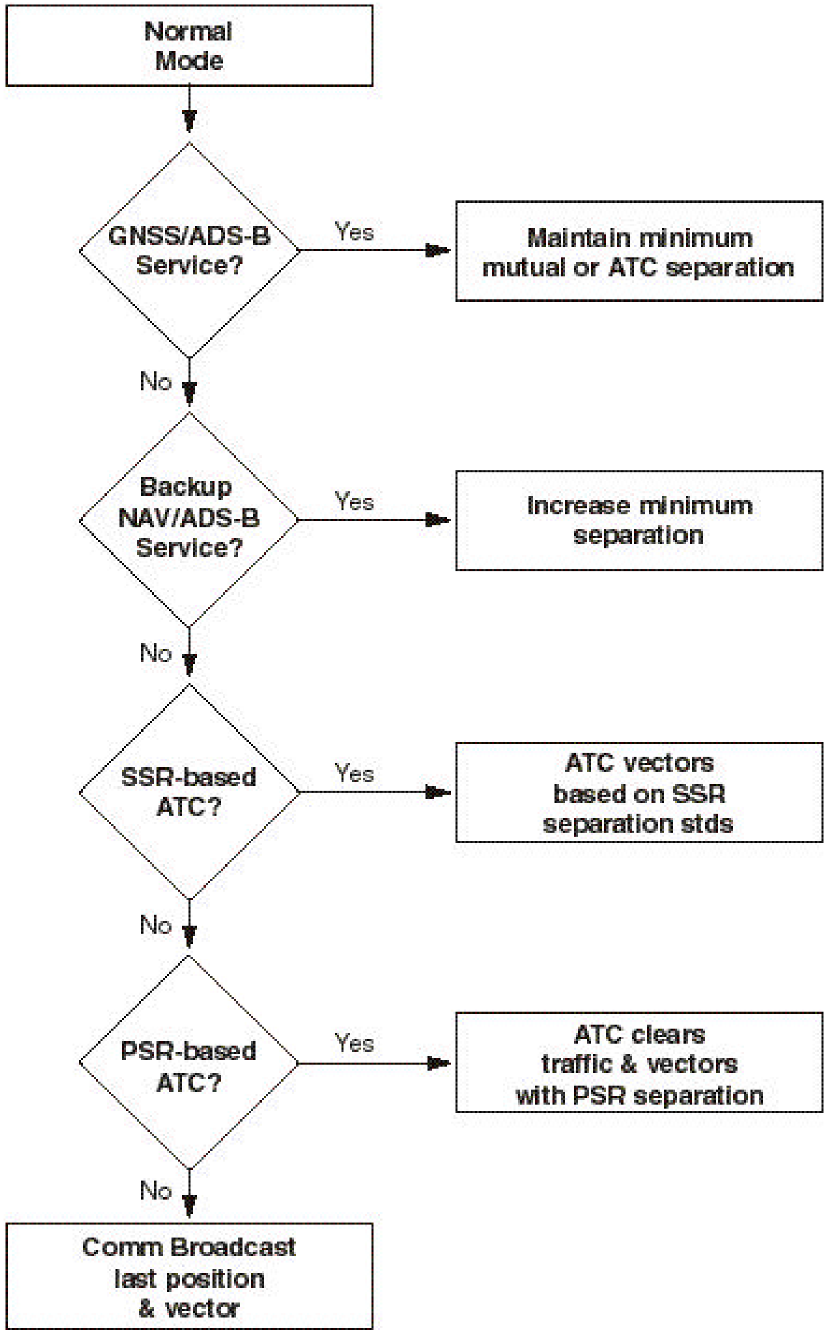


Figure 3.3-2. GNSS/ADS-B Surveillance/Navigation Failure Recovery Modes

3.3.6.3 ADS-B Availability Requirements

Availability is calculated as the ADS-B System Mean-Time-Between-Failures (MTBF) divided by the sum of the MTBF and Mean-Time-To-Restore (MTTR). ADS-B equipage is defined to be available for an operation if the following conditions are met: (1) ADS-B equipage outputs are provided at the rates defined in Table 3.3-3 and (2) the ADS-B reports have the integrity required by Section 3.3.6.5, For the purposes of calculating availability, an ADS-B transmission subsystem is considered to be one participant's message generation function and message exchange (transmission) function. An ADS-B receiver subsystem is considered to be one participant's message exchange (receiver) and one report generation function.

ADS-B availability shall (R3.24) be 0.9995 for class A0 through class A3 and class B0 through class B3 transmission subsystems. ADS-B availability shall (R3.25) be 0.95 for class A0 receiver subsystems. Class A1, A2, and A3 receiver subsystems shall (R3.26) have an availability of 0.9995. Specification of Class C receiver subsystem availability requirements are beyond the scope of this MASPS.

High transmission availability (0.9995) is required of all classes in order to support the use of ADS-B as a primary means of surveillance for ATS. The combination of 0.9995 availability of transmission and 0.9995 availability of receive for classes A1 through A3 results in availability of 0.999, allowing the use of ADS-B as a primary means of surveillance for some air-to-air operations. A lower availability is permissible for Class A0 receiver subsystems as ADS-B is expected to be used as a supplemental, rather than as a primary tool of separation, for this class.

3.3.6.4 ADS-B Continuity of Service

The probability that the ADS-B System, for a given ADS-B Message Generation Function and in-range ADS-B Report Generation Processing Function, is unavailable during an operation, presuming that the System was available at the start of that operation, shall (R3.27) be no more than 2×10^{-4} per hour of flight. The allocation of this requirement to ADS-B System Functions should take into account the use of redundant/diverse implementations and known or potential failure conditions such as equipment outages and prolonged interference in the ADS-B broadcast channel.

3.3.6.5 ADS-B Integrity

ADS-B integrity is defined in terms of the probability of an undetected error in a report received by an application, given that the ADS-B system is supplied with correct source data. The integrity of the ADS-B System shall (R3.28) be 10^{-6} or better on a per report basis. Appendix I contains information relevant to the development of high integrity end-to-end surveillance, conflict detection and management, and separation assurance applications using ADS-B.

Demonstration of compliance with ADS-B System integrity requirements will require a safety assessment to evaluate the System's implementation against known or potential failure conditions such as encoding, decoding and processing errors and interference in the ADS-B channel.

Appendix G, Attachment 3

Eurocontrol ADS Programme proposed criteria for ADS-B Datalink technical assessment

1. Introduction

This note describes criteria for ADS-B data links that will be used to assist in the assessment of the performance of those links. The criteria are proposed in addition to the ones which are already used and are based on the ADS-B MASPS.

The purpose of these criteria is to provide input to the Eurocontrol/FAA TLAT activity that is currently gathering information on ADS-B data link performance.

These proposed criteria reflect the Eurocontrol ADS Programme current knowledge and expert opinion about factors that are of interest in ADS-B data link operation in Europe and therefore should be considered in the assessment. These criteria are meant to allow a margin for evolution of the ADS-B system to meet also future needs.

2 Applications

2.1 ATS Surveillance

This is the extension of the current classical Surveillance service in an ADS-B environment, e.g. Managed Airspace/Continental/Medium and Low-Density. The use of trajectory intent information is also foreseen.

	ATS SUR	Notes
TYPE OF AIRSPACE		
Managed Airspace/Medium and Low Density	✔[1]	
FLIGHT PHASE		
TMA	✔	
En-Route	✔	
DATA ITEMS		
Identification		
Call Sign	✔	
24-bit Address	✔	
Time	✔	
3-D Position		
Latitude	✔	
Longitude	✔	
Altitude	✔	
Estimated Position Uncertainty	✔	
Status	✔	Based on the RTCA MASPS definition
Intent		To support intent based ATM, including MTCD, conformance monitoring etc.
Trajectory Change Point (TCP)	✔	
TCP+1	✔	
TCP+2	✔	
TCP+3	✔	
Capabilities indication	✔	
Future Expansion	✔	

[1] ✔ : Required

TRANSMISSION CHARACTERISTICS (Periodic/ Effective Update Period) Event Driven/Event Type for TCP changes) Probability of update within period	Periodic 5 sec (TMA) & 10 sec (En-Route) for position 5 min for “no-change of TCPs” indication & Event driven for TCPs (On acquisition and on change) Allowing reception within 24 sec with 95% confidence >98%	
PERFORMANCE REQUIREMENTS Operational Range		60 nm for TMA 150 nm for En-Route per single ground station
Operational Traffic Densities (#a/v<Range (nm))		Based on the scenarios for 2005, 2010, 2015
Accuracy	At least equivalent to SSR accuracy	Calculations to be made based on Eurocontrol Surveillance Std (Section 6.3.3) or RTCA MASPS, p. 57

2.2 ATS Enhanced Surveillance

This is an application based on the extension of the Mode S Enhanced Surveillance, as currently envisaged, for the core area of Europe.

	ATS Enh. SUR	Notes
TYPE OF AIRSPACE		
Managed Airspace/High-Density	✔	
FLIGHT PHASE		
TMA	✔	
En-Route	✔	
DATA ITEMS		
Identification		
Call Sign	✔	
24-bit Address	✔	
Time	✔	
3-D Position		
Latitude	✔	
Longitude	✔	
Altitude	✔	
Estimated Position Uncertainty	✔	
Velocity		
Ground Speed	✔	
Track Angle	✔	
Airspeed	✔	
Heading	✔	
Vertical Rate	✔	
Track Angle Rate	✔	

Status	✔	
Intent		To support intent based ATM, including MTCD, conformance monitoring etc.
Selected Altitude	✔	
Trajectory Change Point (TCP)	✔	
TCP+1	✔	
TCP+2	✔	
TCP+3	✔	
Capabilities	✔	
Future Expansion	✔	
TRANSMISSION CHARACTERISTICS (Periodic/ Effective Update Period - Event Driven/Event Type for TCP changes) Probability of update within period	Periodic 5 sec (TMA) & 10 sec (En-Route) for position, state vector 5 min for "no-change of TCPs" indication & Event driven for TCPs (On acquisition and on change) Allowing reception within 24 sec with 95% confidence >99%	
PERFORMANCE REQUIREMENTS		
Operational Range		60 nm for TMA 150 nm for En-Route per single ground station
Operational Traffic Densities (#a/v<Range (nm))		Based on the scenarios for 2005, 2010, 2015
Accuracy	At least equivalent to SSR Mode S accuracy	Calculations to be made based on POEMS Specifications or RTCA MASPS, p. 57

2.3 A-SMGCS

This application is supposed to include runway incursion functionality and is not limited within the airport surface area.

	SMGCS	Notes
TYPE OF AIRPORT		
High-Density	✔	
Low-Density	✔	
FLIGHT PHASE		
Taxi	✔	
TMA	✔	
DATA ITEMS		

Identification		
Call Sign	✔	
24-bit Address	✔	
Emitter Category	✔	
Time	✔	
3-D Position		
Latitude	✔	
Longitude	✔	
Altitude	✔	Not required if there is “on-ground” indication
Estimated Position Uncertainty	✔	
Velocity		
Ground Speed	✔	
Track Angle	✔	
Vertical Rate	✔	Not required if there is “on-ground” indication
Estimated Velocity Uncertainty	✔	
Status	✔	
Capabilities	✔	
Future Expansion	✔	
TRANSMISSION CHARACTERISTICS (Periodic/ Effective Update Period - Event Driven/Event Type)	Periodic 1.5 sec for 0-5 nm range 3 sec for 5-10 nm range (95%)	
PERFORMANCE REQUIREMENTS		
Acquisition Range (nm)	10	
Operational Traffic Densities (#a/v<Range (nm))		Based on the scenarios for 2005, 2010, 2015
Accuracy	Sigma,hp= 2.5 m Sigma,hv= 0,3 m/s	

2.4 Autonomous Operations

The number of TCPs to be transmitted[2] should be 4, i.e. up to and including TCP+3. The range should be the one which was used for the applications above, i.e. in the order of 150 nm.

3. Transmission Characteristics

As implied from the description of the relevant characteristics of the applications above, the proposed criteria include also the assessment of the potential of the candidate technologies to support an *event driven transmission*, e.g. in the case of TCPs. Individual technologies should opt for a periodic or an event driven TCP transmission, but in all cases they should meet the update requirements stated in the previous section.

[2] Based on Eurocontrol simulations

Appendix H: Traffic Scenarios

This appendix addresses assumptions used in the link characterization regarding the traffic scenarios and the operational environment.

Traffic Scenario Assumptions

For the ADS-B data link evaluation, there are a total of three air traffic scenarios which have been approved by the TLAT for assessing data link technical performance. Two of these scenarios involve specific geographic areas (Core Europe and Los Angeles Basin), each assessed for a projected future time period (2020 for the Los Angeles Basin and 2015 for Core Europe). The two airspace regions are quite different in character, which will provide two diverse views of the data link performance. The third scenario is intended to model lower density airspace (which is representative of the majority of the world's airspace). The LET has generated three sets of aircraft, one for each of the data link scenarios, for common use in the evaluation of the three system candidates. Figure H-1 depicts the total traffic for each scenario as a function of range, as well as current estimates of maximum traffic for the Los Angeles Basin (1999) and Core Europe (2005).

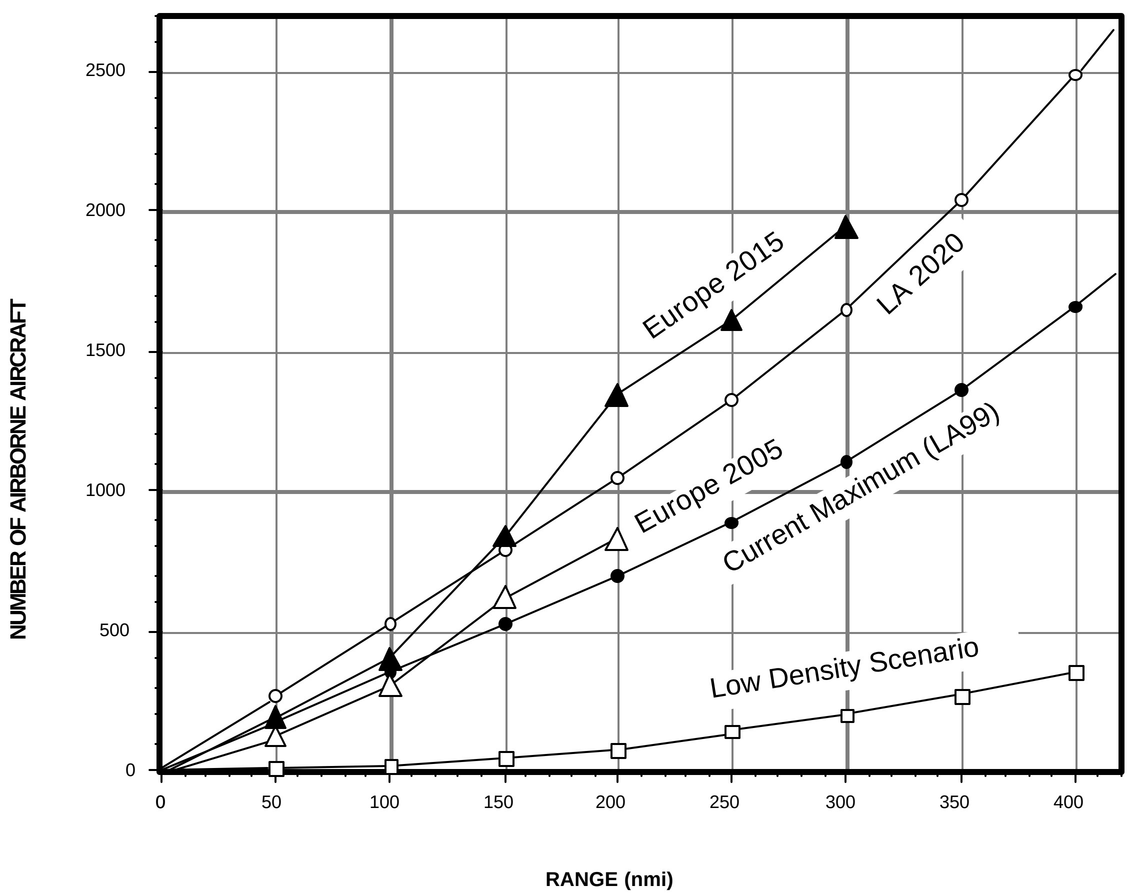


Figure H-1: Cumulative range distributions for the five aircraft traffic scenarios.

The data plotted in Figure H-1 is given numerically in Table H-1.

Table H-1. Number of airborne aircraft and range distributions.

	RANGE							
	50 nmi	100 nmi	150 nmi	200 nmi	250 nmi	300 nmi	350 nmi	400 nmi
LA 99	175	350	525	700	883	1103	1362	1661
LA 2020	257	532	797	1071	1312	1655	2054	2469
Europe 2005	124	306	622	826				
Europe 2015	188	404	836	1348	1613	1942		
Low density	6	23	51	90	141	203	276	360

Los Angeles Basin 2020

This scenario was based on the Los Angeles Basin 1999 maximum estimate. It was assumed that air traffic in this area would increase by a few percent each year until 2020, when it would be 50 % higher than in 1999.
The following assumptions went into generating the airborne and ground aircraft for the Los Angeles Basin 2020 scenario:

- The density of airborne aircraft was taken to be:
  - Constant in range from the center of the area out to 225 nautical miles (5.25 aircraft/nm), (i.e., the inner circle of radius one nm would contain approximately five aircraft, as would the ring from 224 to 225 nm) and
  - Constant in area from 225 nm to 400 nm (.00375 aircraft/nm^2).
- There were assumed to be a fixed number of aircraft on the ground (within a circle of radius 5 nm at each airport), divided among LAX, San Diego, Long Beach, and five other small airports. Half of the aircraft at each airport were assumed to be moving at 15 knots, while the other half were stationary.
- The altitude distribution of the airborne aircraft was assumed to be exponential, with a mean altitude of 5500 feet. This distribution was assumed to apply over the entire area.
- The airborne aircraft were assumed to have the following average velocities, determined by their altitude. The aircraft velocities for aircraft below 25000 feet will be uniformly distributed over a band of average velocity +/- 30 percent.
  - 0-3000 feet altitude 130 knots
  - 3000-10000 ft 200 knots
  - 10000-25000 ft 300 knots
  - 25000-up 450 knots
- The aircraft are all assumed to be moving in random directions.
- All aircraft above 10000 feet are assumed to be either ADS-B MASPS equipage class A3 (75%) or A2 (25%) (for further definition of the equipage classes, see RTCA DO-242, Table 3-3a), while below 10000 feet, the ratios are adjusted to give the entire ensemble of aircraft the following proportions of equipage:
  - A3 30%
  - A2 10%
  - A1 40%
  - A0 20%

The scenario for the 2020 high density LA Basin case contained a total of 2694 aircraft: 1180 within the core area of 225 nm, 1289 between 225-400 nm, and 225 on the ground. This represents a scaling of the estimated maximum 1999 LA Basin levels upward by 50 percent. Of these aircraft, 471 lie within 60 nm of the center. (This includes aircraft on the ground.) Around ten percent of the total number of aircraft are above 10000 ft in altitude, and more than half of the aircraft are located in the outer (non-core) area of the scenario.

An attempt was made to at least partially account for the expected lower aircraft density over the ocean. In the third quadrant (between 180 degrees and 270 degrees), for distances greater than 100 nm from the center of the scenario, the density of aircraft was reduced to 25 % of the nominal value used. The other 75 % of aircraft which would have been placed in this area were distributed uniformly among the other three quadrants at the same range from the center. This results in relative densities of 1:5 between the third quadrant and the others.

Core Europe 2015

For the Core Europe 2015 scenario, the distributions and assumptions made were taken directly from the Eurocontrol document entitled "High-Density 2015 European Traffic Distributions for Simulation," dated August 17, 1999. This scenario is fairly well-defined and straightforward to apply.

This scenario includes a total of 2091 aircraft (both airborne and ground), and is based on the following assumptions:

- There are five major TMAs (Brussels, Amsterdam, London, Paris, and Frankfurt), each of which is characterized by:
    - The inner region (12 nm radius) contains 29 aircraft at lower altitudes,
    - The outer region (50 nm radius) contains 103 aircraft at mid to higher altitudes.
    - There are assumed to be 25 aircraft on the ground, within a 5 nm radius, plus another 25 aircraft randomly distributed throughout the entire scenario area.
- These aircraft are assumed to be symmetrically distributed rotationally, and the aircraft in an altitude band are assumed to be uniformly distributed throughout the band. However, all aircraft in the same band are assumed to be travelling at the same band-dependent velocity.
- Superimposed over these aircraft is a set of airborne en route aircraft, which are distributed over a circle of radius 300 nm. These aircraft are distributed over four altitude bands, ranging from low to upper altitudes. They also travel at velocities which are altitude band dependent.
- As in the Los Angeles Basin 2020 scenario, for the Core Europe 2015 scenario all aircraft are assumed to be ADS-B equipped. The equipage levels have been adjusted to be:
    - 30 % A3
    - 30% A2
    - 30% A1
    - 10% A0
    - 50% of the A0 and A1 aircraft are considered to be General Aviation

Aircraft equipage is assigned according to altitude. The lower percentages of A0 and A1 aircraft than those found in the LA Basin scenarios reflect differences in operating conditions and rules in European airspace.

The two geographical areas which underlie the scenarios discussed above (Los Angeles Basin and Core Europe) correspond to very different types of situations for an aircraft to operate in, and thus should provide two diverse environments for evaluation. The Los Angeles Basin scenario contains only about 14% of all airborne aircraft at altitudes above 10000 ft, while the Core Europe scenario has around 60% above 10000 ft. Thus, there will be vastly different numbers of aircraft in view for the two scenarios. Additionally, the aircraft density distributions are also quite different, which will place different stresses on the data link systems.

Low Density

For simplicity, the number of aircraft for the third scenario was set by scaling the current maximum Los Angeles Basin levels downward by a factor of five, amounting to 360 total aircraft. These aircraft are uniformly distributed in the horizontal plane within a circle of 400 nautical miles. In the vertical direction, they are distributed uniformly between 25,000 feet and 37,000 feet. The velocities are all set to 450 knots and are randomly distributed in azimuth. All of the aircraft are assumed to be A3 equipped.

The TLAT is of the view, using engineering judgement, that adding additional aircraft density to the future LA Basin or Core Europe 2015 scenarios is not likely to provide further discrimination between the ADS-B link candidates. Should this prove not to be the case, one or more scenarios with greater density would have to be evaluated. The TLAT simulations showed (see Appendix K) that all three links were saturated at the postulated scenarios for Los Angeles 2020 and Core Europe 2015.

Appendix I

Data Link Receiver Performance Models

Background

The large-scale system simulation (LCSS) is used to evaluate the ability of each candidate data link to meet the ADS-B performance requirements under various scenarios described by the geographic density and distribution of aircraft. In doing so, the LCSS determines message reception performance by computing the received strength and arrival time of the signals and interference arriving from aircraft transmitters. For the receiver location(s) under evaluation, a data link Receiver Performance Model (RPM) is used to determine, from these data, the probability of reception for each transmitted message. Since the interference environments and reception performance of the three candidate data links are quite different, a separate RPM was developed for each.

This appendix describes the RPMs of the three candidate data links used in the ADS-B data link evaluation.

Receiver Performance Model Description

The receiver performance models provide a probability of receipt for each message reception opportunity described in the model inputs. In general, the model inputs are

(a) the desired signal level (dBm),

(b) the receiver sensitivity, typically characterized by the signal level required to achieve 10% Message Error Rate (MER) in the absence of any other interference, and

(c) an interference characterization which includes, in general, separate information for each interfering transmission, such as type, level, start time offset relative to the desired signal, and carrier frequency offset relative to the desired signal.

The RPMs were developed based on replicating the results of receiver laboratory testing carried out at APL. As such, the models include most (but not all) characteristics of actual data link receiver implementations.[1]

Depending on the link type evaluated, the LCSS is customized to provide the specific inputs required by the associated receiver performance model. For the UAT and VDL-4 simulations, both the desired signal and any interfering signals are assumed to be UAT (or co-channel VDL-4) transmissions, and interferers are assumed to have no carrier frequency offset relative to the desired signal and one another. For the 1090 model, the interfering signals are assumed to be ATCRBS and Mode S (both short and extended squitters), and signal and interferer have a randomly chosen frequency offset relative to one another.

[1] Some observed characteristics were obvious implementation flaws, errors, or limitations that would not be expected in an operational system. Such characteristics were not included in the receiver performance models.

The primary goal of data link laboratory testing is to fully characterize message reception performance in noise and interference. These data serve as the basis for the data link receiver performance models.

While having the equipment in the lab, it was decided to perform as complete a characterization as practical so that the resulting radio models could include other characteristics beyond basic message reception performance. Specific technical objectives of the laboratory testing were:

1) *Measure the message error rate (MER) performance in background noise and co-channel interference*. Test data is needed in order to develop a model that gives probability of correct message receipt for any given signal-noise power ratio (SNR) and signal-undesired signal power ratio. For Mode S Extended Squitter, testing was carried out to characterize performance in all of the major interference types that can be expected - Mode A/C (replies to ATCRBS and TCAS interrogations), Mode S Short Squitters, and ADS-B Mode S Extended Squitters. Further, for all data links, dependence of MER performance on amount of time overlap between desired and undesired signals was measured.

2) *Evaluate electromagnetic compatibility of data links with current airborne navigation and communication systems.* Measure adjacent and co-channel MER performance for VDL Mode 4. Measure transmitted spectrum for all three data link candidates to provide information needed for establishing MOPS and to help evaluate data collected during field testing.

3) *Measure impact of other equipment implementation characteristics on MER performance*. These tests support development of more realistic data link models, and support evaluation of data collected during field testing. Such measurements include receiver recovery time, variations in performance between different transmitters and receivers, and variations in RF signal loss on different aircraft installations. It is expected that data from these tests will prove useful in developing technical requirements for the MOPS once a data link is selected for ADS-B.

The attachments to this appendix are presentations that document the receiver performance laboratory testing. Short summaries of the briefings follow:

<u>1090 Receiver Lab Test Results: LDPU</u>. Results of lab Message Error Rate (MER) testing conducted at JHU/APL during June – November 2000, which characterized in detail the performance of the UPS-AT Link Display Processing Unit (LDPU) 1090 Extended Squitter receiver against noise and 1090 MHz interference (ATCRBS, short squitters, and extended squitters). Interference test results are for presented for single and multiple (up to 7) simultaneous interferers, varying degrees of interference-signal time overlap, and different interference frequency (relative to desired signal). Receiver sensitivity was evaluated with and without the antenna pre-amp. Probability of Undetected Message Error (PUME) was also measured under selected conditions.

<u>VDL Mode 4 Lab Testing: ADSI Radios</u>. Results of lab Message Error Rate (MER) testing conducted at JHU/APL during June – August 1999, which characterized in detail the performance of the ADSI VDL Mode 4 radio against noise and VDL-4 interference. Some

parameters were varied to simulate realistic conditions and further characterize performance, including signal and interference frequency to simulate doppler, interference located in adjacent frequency channels, and amount of interference-signal time overlap to simulate differential propagation delay. Receiver sensitivity and MER performance of several different receivers was evaluated to assess impact of manufacturing variability on performance. Additionally, the transmit spectrum and output power were measured.

UAT Lab Testing: LDPU Radio. Results of lab Message Error Rate (MER) testing conducted at JHU/APL during September 1999, which characterized in detail the performance of the UPS-AT LDPU Universal Access Transceiver (UAT) receiver against noise and UAT interference. Tests conduct and types of results are similar to VDL-4 testing.

Appendix J:
Summary of ADS-B/Situational Awareness Link Modeling and Simulation

Introduction

ADS-B information exchange capabilities in various operational environments are determined by a number of factors: pair-wise radio link signal level limitations, ADS-B message format features, receiver and message decoder characteristics, the radio net access protocol employed, the number and distribution of users within detection range sharing this net, and message broadcast rates for each of these units. The high traffic densities forecast for future scenarios preclude operational evaluation of any proposed system design in these future environments. A shared channel concept faces the additional requirement of representing the future co-channel interference levels associated with multiple use of the channel. For example, the need to emulate future Secondary Surveillance Radar (SSR) and Traffic alert and Collision Avoidance System (TCAS) associated interference levels on the shared use 1090 Mhz channel restricts flight tests of this alternative in any environment other than those existing today.

Analytical models and detailed simulations of proposed designs operating in future scenarios are therefore required to assess expected capabilities in stressed circumstances. Accurately modeling future capabilities for different designs in a fair way, however, is challenging. Since validation of simulation results in future environments is unrealistic, other means of verification such as those discussed in the following are required. System characteristics represented in these simulations should agree with actual measurements on components of the proposed design, e.g., bench measurements on prototype equipment and calibrated flight test data should be used for the receiver/decoder capabilities and as comparison with modeled link budgets. Similarly, flights monitoring interference levels associated with current SSR and TCAS, coupled with a suitable interference model, support estimates of how these conditions may change in future scenarios. Credibility of any simulation results for future scenarios also requires that they be able to model current conditions and provide results that appropriately agree with measurements made under these conditions. Existing tools have been used as cross-checks where possible for the final detailed simulations and models.

General Assumptions

In an effort to capture as many real-world effects important to the assessment of the three data link candidates as possible, an attempt was made for each of the detailed simulations to include, to the extent possible, representations of the effects of:

- Propagation and other losses
- Antenna gains
- Propagation delays
- Co-channel interference
- Co-site interference (in and out of band)
- Multiple interference sources
- Alternating transmissions between top and bottom antennas
- Receiver diversity
- Transmit power variability
- FIS-B data transmissions
- Receiver retriggering
- Receiver performance based on bench testing

Although the original goal was to include all of these effects in each of the models in an equivalent fashion, there were some impediments to doing this, and there were some compromises. Table J-1 below summarizes the levels to which each of the detailed simulations accommodated these effects. The sections below will address some of the implementation techniques, as well as those effects which were not included in a particular simulation. Discussion will include the expected consequences on the results and any projected limitations of the implementations of the effects.

	UAT	1090 Extended Squitter	VDL Mode 4
Losses	Free-space prop loss + 3dB cable loss	Free-space prop loss + 3 dB cable loss	Free-space prop loss + 3 dB cable loss
Antenna Gains	As described	As described	As described
Prop delays	Free-space delay	Free-space delay	Free-space delay
Co-channel Interference	UAT	Mode S, ATCRBS, TCAS, 1090 ES	VDL Mode 4
Co-site Interference	Mode S, ATCRBS, DME, TCAS	Mode S, ATCRBS, TCAS, 1090 ES	None
Multiple Interferers	Yes	Yes	Yes
Alternating Transmissions	Yes	Yes	Yes
Receiver Diversity	Yes	Yes	Yes
Transmit Power Variability	Yes	Yes	Yes
FIS-B	No	Yes	Yes
Retriggering	Yes	Yes	Yes
Receiver Performance Model	Based on bench tests	Based on bench tests	Based on bench tests

Table J-1: Simulation capabilities

UAT Detailed Simulation Description and Limitations

The UAT detailed simulation is written in C and allows for horizontal, constant-velocity motion of the aircraft in the scenario, if the user so chooses. The simulation reads in the inputs specifying the particular case to be run, generates all of the ADS-B transmissions and interference, calculates levels and times of arrival for these transmissions, and determines the corresponding message error rates for each ADS-B transmission by all aircraft within line of sight of the victim receiver. This information is then written to an output file, one entry line for each ADS-B transmission, which is then analyzed by post-simulation software. Each of the effects listed above will now be discussed in turn.

<u>Propagation and other losses.</u> The UAT simulation calculates the free-space propagation loss for each transmission, using the range between transmitter and receiver at the time of transmission. There is also a receiver cable loss of 3 dB incorporated in the calculation. An optional transmit cable loss is also included in the simulation, but since the transmit powers have been defined at the antenna, the transmit cable loss has been set to zero for this study.

<u>Antenna gains.</u> The antenna gain model described below has been included in the UAT simulation.

<u>Propagation delays.</u> The propagation delay incurred by the signal in traversing the free space between transmitter and receiver has been included in the UAT simulation.

<u>Co-channel interference.</u> Although the UAT transmission protocol specifies that a transmission begin on one of a fixed number of message start opportunities, the propagation delay described above will cause the

arrivals of messages at the victim receiver to be quasi-random. There may be a number of messages overlapping one another, and these overlaps will be for variable amounts of time. This interference is accounted for in the model.

<u>Co-site interference.</u> Co-site transmissions of UAT messages, DME interrogations, Mode S interrogations and replies, whisper-shout interrogations, and ATCRBS replies are all modeled as interference in the UAT simulation. All of these are treated as "self-interference," and the message error rate of any UAT ADS-B message will be set to one for a total self-interference time greater than 30 microseconds.

<u>Multiple interference sources.</u> Multiple UAT interferers are treated in the receiver performance model by combining their interference levels in a way consistent with bench test measurements. The simultaneous presence of UAT interference and self-interference is also considered by the model.

<u>Alternating transmissions.</u> The model simulates the alternating transmission sequence specified in the system description, TTBBTTBB…, where T = top and B = bottom.

<u>Receiver diversity.</u> The model calculates the signal-to-interference ratio at the top and bottom receive antennas and selects the higher value for message processing.

<u>Transmit power variability.</u> The transmit power for an aircraft is chosen from a uniform distribution given by the limits specified in the system description for the aircraft equipage.

<u>FIS-B data transmissions.</u> Since the UAT system description specifies that the ground uplink transmissions occur in a separate, guarded time segment than the air-to-air transmissions, FIS-B should not interfere with the ADS-B transmissions of the aircraft. Therefore, the simulation does not model this data load.

<u>Receiver retriggering.</u> The UAT simulation checks each individual ADS-B message arriving at the victim receiver for its message error rate. This procedure amounts to allowing for retriggering in the receiver.

<u>Receiver performance model.</u> The receiver performance model described in Appendix I is used in the UAT simulation.

There do not appear to be any specific issues or limitations with the UAT simulation.

VDL Mode 4 Detailed Simulation Description and Limitations

The VDL Mode 4 detailed simulation is called STDMA Performance Simulator (SPS) and is written in Matlab. It does not easily allow motion of the aircraft in the scenario, and has a number of other limitations, which will be described below. SPS reads in the inputs specifying the particular case to be run, generates all of the ADS-B transmissions, calculates signal levels for each transmission, and determines the corresponding message error rates for each ADS-B transmission by all aircraft within line of sight of the victim receiver. This information is then written to an output file, one entry line for each ADS-B transmission, which is then analyzed by post-simulation software. Each of the effects listed above will now be discussed in turn.

<u>Propagation and other losses.</u> SPS calculates the free-space propagation loss for each transmission, using the range between transmitter and receiver which does not vary during the simulation, since there is no motion. There is also a receiver cable loss of 3 dB incorporated in the calculation.

<u>Antenna gains.</u> The antenna gain model described below has been included in the VDL Mode 4 simulation.

<u>Propagation delays.</u> Since SPS deals in slots, rather than time, it was not useful to add propagation delays. The VDL Mode 4 message structure allows for a guard time which corresponds to around a 205 nautical mile difference in range resulting from propagation delays. However, due to the long distance capability of

VDL Mode 4, it is possible to have a situation where the guard time is insufficient to ensure non-interference between successive slots. This circumstance has been investigated and is described below.

Co-channel interference. The VDL Mode 4 slot selection process attempts to minimize slot collisions, but a high-density scenario will inevitably produce collisions in a self-organizing system. The strategy in VDL Mode 4 is to try to confine collisions to occur primarily between aircraft that are far apart. In the SPS version used in this study, the transmission with the strongest signal in the slot is assumed to be the one the receiver will try to receive, while the others are regarded as interference.

Co-site interference. It is assumed that there is no co-site interference to VDL Mode 4.

Multiple interference sources. Multiple VDL Mode 4 interferers are treated in the receiver performance model by simply combining their interference levels and treating the sum as a single interferer. This is consistent with the bench test measurements.

Alternating transmissions. The model simulates the transmission sequence specified in the system description, alternating transmissions between top and bottom antennas.

Receiver diversity. The model calculates the signal at the top and bottom receive antennas and selects the higher value for message processing.

Transmit power variability. The transmit power for an aircraft is chosen from a uniform distribution given by the limits specified in the system description for the aircraft equipage.

FIS-B data transmissions. The system description specifies that FIS-B transmissions will require 240 slots per minute on a global signaling channel (GSC) in the LA Basin scenario. It also says that 240 slots per minute are reserved on the other GSC for its transmissions in all scenarios. Therefore, four slots per second have been reserved for ground station transmissions on one of the GSCs in Core Europe, and on both of the GSCs in the LA Basin.

Receiver retriggering. The issue of retriggering is difficult to handle in SPS. By looking at the strongest signal in each slot, one aspect of retriggering is being addressed. However, the issue mentioned under "propagation delay" is discussed below.

Receiver performance model. The receiver performance model described in Appendix I is used in SPS.

There are a number of unaddressed issued in the implementation of SPS used in this study. One of the most significant is the limitation of single channel simulation by SPS. Since multiple channels may not be run in a single SPS run, and up to four channels are required for the high density scenarios, there is no way of coordinating the transmissions and receptions on the multiple channels. The individual channels have to be run separately, and therefore have no correlation among the channels. This makes it difficult to evaluate a number of expected behaviors. For example, it is assumed for all the links that a platform cannot receive a message while it is transmitting its own ADS-B message. However, since SPS can only handle one channel at a time, there is no way of coordinating this information among the different channels. This may be expected to lead to more optimistic results than would otherwise be the case.

Another consequence of single-channel runs is that the timing of message transmissions cannot be coordinated among the channels. For example, an aircraft in the regional area is expected to transmit on three channels at rates of one, one, and ten transmissions per minute, respectively. Normally, it is expected that the system will space these 12 transmissions at approximately five-second intervals, in order to achieve a consistent transmission rate. However, when a run is made for a single channel at a rate of ten per minute, SPS will space these transmissions at six-second intervals. Merging these data with that from the other two channels then becomes more of a problem, if the goal is to achieve the five-second rate.

SPS is not set up to handle the transmission of a two-slot message required by the system description, so two-slot messages were modeled as two single-slot messages. Appendix M.2 contains a discussion of the expected effect of this modeling assumption. Generally speaking, it is expected that it would be more difficult to find two consecutive slots for transmission than to find two single slots. In processing the two-slot messages, the model assumed that both messages had to be received successfully, in order to receive the two-slot message; therefore, the probability of message receipt was calculated as the product of the two probabilities for receipt for each of the one-slot messages.

One issue referred to above, in the sections on propagation delay and receiver retriggering, is the case of a distant (low signal) transmitter occupying a slot, followed by a nearby (high signal) transmitter in the subsequent slot. If the distant transmitter is more than 205 nautical miles further away than the nearby transmitter (guard time), the messages will overlap and the distant transmission should not be received, since it will be interfered with by a stronger signal, which will cause retriggering of the receiver. SPS only looks at slots, disregarding the potential of slot overrun, thus ignoring the possibility that the nearby signal in the next slot would affect the earlier distant one. It would record the distant transmission as being received (in the absence of interference in its slot). In order to determine the magnitude of the problem, the results from the LA GSC were examined, which is the worst case for slot occupancy. We looked for cases which consisted of the following:

- A slot with a transmitter having a probability of successful message receipt greater than 0.2, followed by a slot with a transmitter <u>at least 205 nmi closer than the transmitter in the previous slot</u>, no matter its probability of successful message receipt.

The result of this search was that this situation occurs 1.4% of the time at the victim receiver in the center of the scenario. Recall that, for purposes of our assessment, aircraft which are this distant are of no interest as far as the evaluation criteria are concerned, but there could an effect on the slot reservation tables in the simulation. This would presumably provide a somewhat optimistic picture of the ability to choose a free slot, although it can certainly be argued that a 1.4% effect is far smaller than other uncertainties.

Finally, no attempt was made to verify that the SPS code dealing with slot selection was SARPS-compliant. We were assured of this by the code developers and found no hard evidence which disputed this. However, the presence of around 20 percent unused slots in the high density scenarios might be a subject of further testing.

1090 Detailed Extended Squitter Simulation Description and Limitations

The 1090 simulation consists of two parts. The first simulation is a C++ program which takes as input the aircraft scenario and a detailed radar interrogator database and produces a time-ordered stream of arrivals of ADS-B messages and other 1090 transmissions at the victim receiver, as well as a stream of co-site transmissions of 1030 and 1090 interrogations and responses. The second simulation consists of two processors. A pre-processor, written in C, takes the output of the first simulation, adds the other interference sources (FIS-B transmissions and DME interference), antenna gains, and signal calculations, and formats it for input into the receiver performance model. Next, the receiver performance processor (written in Matlab) takes the pre-processor output and applies the receiver performance model to determine the message error rate for each ADS-B message. The resulting output is then analyzed with the post-simulation software. As with the other two simulations, each of the effects listed above will now be discussed in turn.

<u>Propagation and other losses.</u> The 1090 simulation calculates the free-space propagation loss for each transmission, using the range between transmitter and receiver at the time of transmission. There is also a receiver cable loss of 3 dB incorporated in the calculation. An optional transmit cable loss is also included in the simulation, but since the transmit powers have been defined at the antenna, the transmit cable loss has been set to zero for this study.

<u>Antenna gains.</u> The antenna gain model described in below has been included in the 1090 simulation.

Propagation delays. The propagation delay incurred by the signal in traversing the free space between transmitter and receiver has been included in the 1090 simulation

Co-channel interference. Since the 1090 transmission protocol is random access, the arrivals of messages at the victim receiver should be random. There may be a number of messages overlapping one another, and these overlaps will be for variable amounts of time. This interference is accounted for in the model. In addition, the arrivals of other transmissions, such as ATCRBS, Mode S, TCAS, and FIS-B are also included in the model as interference.

Co-site interference. Co-site transmissions of 1090 Extended Squitter messages, DME interrogations, Mode S interrogations and replies, whisper-shout interrogations, and ATCRBS replies are all modeled as interference in the 1090 simulation.

Multiple interference sources. The time-sequence of all sources of interference is considered for each ADS-B message, and all overlapping interference is fed into the receiver performance model along with the ADS-B message to produce the resulting message error rate. The receiver performance model treatment of multiple interference sources is based on the results of bench tests of multiple sources of interference.

Alternating transmissions. The model simulates the alternating transmission sequence between top and bottom antennas specified in the system description. This is a complex process and depends on the message type being transmitted.

Receiver diversity. The model calculates the signal levels at the top and bottom receive antennas and selects the higher value for message processing.

Transmit power variability. The transmit power for an aircraft is chosen from a uniform distribution given by the limits specified in the system description for the aircraft equipage.

FIS-B data transmissions. In the LA Basin scenario, the 1090 simulation models a network of ground stations on a 60 nautical mile hexagonal grid. These ground stations are each transmitting ten extended squitters per second to represent the FIS-B data load. They appear at the victim receiver and are treated by the simulation as interference.

Receiver retriggering. The 1090 simulation checks each individual ADS-B message arriving at the victim receiver for its message error rate. This procedure amounts to allowing for retriggering in the receiver.

Receiver performance model. The receiver performance model described in Appendix I is used in the 1090 simulation.

There are no major limitations that have been discovered for the 1090 simulation chain.

Simulation Model to Represent Aircraft Antenna Gains

A top mounted aircraft antenna provides useful coverage in horizontal directions and in upward directions, but significantly weaker signals in downward directions. The reverse is true for a bottom mounted antenna. Furthermore an aircraft antenna exhibits smaller but significant nonuniformities in azimuth. Differences from aircraft to aircraft are also to be expected. TLAT developed an antenna-gain model in order to incorporate these effects in all three simulations. The model includes an elevation-angle dependence that represents the complementary nature of top and bottom antennas. The model also includes variability in azimuth and from aircraft to aircraft. The specifics in this model were based on a large number of model aircraft measurements (ref. F-4, appendix C). The following formulas define the aircraft antenna gain model used in the TLAT evaluations. This model was used in simulating all three systems.

For each antenna (top and bottom, transmit and receive) antenna gain with respect to a particular other aircraft is modeled as the sum of two components, G1 a function of elevation angle, and G2 a random component (to characterize fluctuations as a function of azimuth, different aircraft shapes, and different antenna locations). Total antenna gain in dB is G =G1 + G2.

(1) The elevation function G1 for a top antenna is

G1(dB) = 10 log g, where

g = 2 / (BW * pi / 180) * exp -((1.66 * (ELEV - PEAK)/ BW)^2

where ELEV = elevation angle in degrees,

PEAK = 26.2 degrees = elevation angle in degrees at the peak.

and BW = 45 degrees = half-power beamwidth in degrees,

For a bottom antenna, the formula is the same except changing PEAK to -26.2 degrees. As the simulation progresses, G1 is calculated continually and therefore changes as elevation angle changes.

(2) The random component G2 is selected independently for each antenna at the beginning of the simulation. The component G2 has a bell shaped distribution, generated as follows. Let x be a random variable, uniformly distributed between 0 and 1. Then

For x<0.327,	G2(dB)=2.76+0.5677*10*log10(x),
For 0.327<=x<0.8,	G2(dB)=-4.8+25.42*x-39.354*x^2+23.333*x^3,
For 0.8<=x	G2(dB)=0.320-.27813*10*log10(1-x).

As the simulation progresses, component G2 remains constant (for each antenna) until azimuth changes by 5 degrees or more. When that happens for a particular aircraft with respect to a particular other aircraft, a new random selection is made for both top and bottom antennas on that one aircraft.

Note that the model does not include any component of short-term variability. Such a component was considered by TLAT in developing the model but was not included.

Note that the benefits of top-bottom diversity are not included explicitly in this model. Since the model includes separate top and bottom antennas, the diversity benefit will be a natural consequence of running the simulation.

Note also that for a particular aircraft antenna, it will have a different value of antenna gain for each of the other aircraft. For example, in a simulation of 100 aircraft, for a particular aircraft the simulation will generate 99 values of gain for the top antenna and 99 values of gain for the bottom antenna for each of the 99 transmitting aircraft. There will also be 99 values of gain for each of the top and bottom receiving antennas.

Appendix K
Trial and Simulation Results

K.1 Trials

Validation by trials of simulation results in future environments is clearly unrealistic, therefore other means of verification of the reasonableness of the results are required. System characteristics represented in these simulations should agree with actual measurements on components of the proposed design, e.g., bench measurements on prototype equipment. Calibrated flight test data should be compared with the modelled link budget and receiver/decoder capabilities. Similarly, flights monitoring interference levels associated with current SSR and TCAS, coupled with a suitable interference model, support estimates of how these conditions may change in future scenarios. Credibility of any simulation results for future scenarios also requires that they be able to model current conditions and provide results that appropriately agree with measurements made under these conditions.

In the years 1999 and 2000, a number of ADS-B flight trials testing the three candidate data links were organised with sponsoring from Eurocontrol, the FAA and other organisations. The TLAT used data collected in these trials for a number of model development and validation purposes:

- as sanity checks on the expected benign performance of the links;
- as indicators of the magnitude of effects, such as antenna gains and interference;
- as a calibration of the 1090 model interference environment calculation; and
- as information characterising receiver performance in the presence of noise and interference

Complementary data measurements came also from laboratory bench testing conducted mainly by JHU APL, FAA Technical Centre, and Eurocontrol Experimental Centre (EEC) to characterise radio equipment performance, and calibrate the equipment for field testing.

The use made of 1999 ADS-B trial results has already been described in the LET report. The following subsections present the 2000 flight trials whose results were also used in the TLAT analysis and validation process.

K.1.1 ADS-B/1090 Ext. Squitter Trials in Frankfurt, Germany, 19-25 May 2000

These trials were organised by DFS, FAA, and Eurocontrol aiming to characterise the ADS-B performance of 1090 MHz Extended Squitter and evaluate the current RF 1030/1090 MHz environment in Frankfurt. The Frankfurt area was selected because it presents one of the highest interference 1090 MHz environments in the world. The high reply rates are caused by a combination of many interrogators (U.S. and German military and German civil interrogators) and very dense air carrier traffic. In 1995, DFS and FAA had conducted similar RF measurements in the same area consequently the 2001 trial results also served to asses how the 1030/1090 RF environment has evolved in the Frankfurt area over the last six years[1].

The primary goals of the Frankfurt trials activity were:

1. Measuring and characterising performance of Mode S Extended Squitter in “worst case operational environment” with very high fruit rates.
2. Evaluating performance of improved Mode S reply processing algorithms.
3. Measuring and characterising use of 1030/1090 MHz surveillance spectrum, both air/air and air/ground in Frankfurt to improve understanding of the results and related mechanisms due to environment, installation or system implementation.
4. Recording data to support simulation model validation

[1] During this period, DFS has been upgrading its ground radar infrastructure converting civil SSR radars (which used sliding window techniques) to monopulse and upgrading in many cases to Mode S radar sensors.

Three project aircraft were used including a Boeing 727 supplied by FAA TC, a Fairchild Metroliner supplied by NLR and a King Air B300 supplied by FII. Up to five targets of opportunity transmitting 1090 ext. squitters were also observed during the trials sessions. These targets were found to be British Airways Boeing 757 aircraft that happened to fly in the Frankfurt area during the trial sessions.

The project aircraft were equipped with 1090 ext. squitter capable transponders (Honeywell or Collins) and UPS AT LDPUs[2] as dual ext. squitter receivers. The FAA TC aircraft carried also RF environment monitoring equipment and TCAS based 1090 ext. squitter receiver. Two separate L-Band omni avionics blade antennas (with inbuilt 15 dB pre-amp) were dedicated on each aircraft to extended squitter reception.

Two ground station sites were established, one at Langen and one at the military base at Wiesbaden. The Langen site was equipped with three different 1090 ext. squitter receiving stations (ANS MAGS, ERA, and UPSAviation Technologies LDPU). All three stations shared the same L-Band antennas (two 66 deg beamwidth directional antennas). The Wiesbaden site had only the UPS-AT receiving station and used two sectors of a six sector L-band antenna (each sector had 60 deg beamwidth). In both sites the received signals were pre-amplified to counter cabling losses.

The following elements were recorded in the flight sessions:

a. <u>1030 MHz interrogation rate</u>, which provides an understanding of the relative contribution of TCAS, ground-based SSR and Mode S sensors to the 1030 MHz channel occupancy.

b. <u>1090 MHz reply and suppression rates</u> in order to generate statistics and get estimates on the 1090 MHz interference environment.

c. <u>Mode S/SSR aircraft positions</u>, to obtain total aircraft count, and traffic density to re-create scenario details to identify specific contributions to the interference environment.

d. <u>Extended Squitter reports</u> from ADS-B aircraft to generate statistics on reception probabilities as functions of range, reply rates and geometry.

e. <u>Aircraft state data</u> (Reception time, GPS or FMS position, pressure altitude, ground speed vector) for background information, scenario re-creation and specific investigations as necessary.

An interim report has been published on the Frankfurt trial results.. The final report is to be issued later in the year 2001. Presentations of the Frankfurt trial interim results were made to the TLAT by Lincoln Labs and Eurocontrol Experimental Centre staff.

The Frankfurt trial data were used by Eurocontrol as follows: Traffic distribution and ground station interrogator scenarios were developed to match the current situation in Frankfurt. These scenarios were run with the DERA SIEM models and the resulting 1090 fruit and 1030 interrogation rates were compared the measurements reported in the Frankfurt trial report. The simulation scenarios also included victim ADS-B receivers placed on the tracks of the Frankfurt trial ADS-B equipped aircraft. The victim receiver ADS-B performance was compared with the measurements made in Frankfurt. The results of these comparisons are described in Appendix K.2.

APL performed similar validation activities for the VOLPE model using Los Angeles Basin 1999 trial data (see Appendix K.2).

[2] The same type of unit was also used in 1999 trials and served as the basis for the development of the 1090 receiver waveform model used in the TLAT simulations.

K.1.2 UAT Trial in Paris, France, 21 Sept to 2 Oct 2000

These flight trials were organised by Eurocontrol with the participation of the FAA Safe Flight 21 Program, Mitre, and UPS Aviation Technologies. UAT operation was tested in the 966 MHz channel, which currently is not used in France. The primary goals of the UAT trials were:

1. Characterizing performance of a/a and a/g UAT operation in an "interference - free" RF channel under various flight geometries.
2. Evaluating performance of the passive range monitoring capability provided by UAT.
3. Demonstrating ADS-B, TIS-B, and FIS-B capabilities offered by the CAPSTONE equipment (including radio, CDTI display and GPS) and the Mitre GBS Ground Station.
4. Comparing with the results of the 1999 UAT trials conducted by Eurocontrol for validation
5. Recording data to support simulation model validation

Two project aircraft were used including a Fairchild Metroliner and a Cessna 550 Citation both supplied by NLR. The Metroliner had also been used in the Frankfurt trial. Both project aircraft were equipped with single CAPSTONE transceivers[3] and UPS-AT MX20 CDTIs. Top and bottom omni passive avionics blade antennas (tuned to 966 MHz) were installed on each aircraft for UAT use.

Two UAT ground stations were established both located at the EEC building, which is very close to the Brétigny aerodrome that served as base for the project aircraft. One station used the Mitre GBS and a UPS-AT LDPU[4] connected to a DME omni antenna and the other used a MX20 CDTI and a CAPSTONE radio connected to an omni 966 MHz avionics blade antenna.

There were in total two flight trial sessions (with both project aircraft participating) and two pre-trial calibration sessions (one per project aircraft). The following elements were recorded in the flight sessions:

a. UAT message reports from the project aircraft to generate statistics on reception probabilities as functions of range and geometry, and test (offline) passive range monitoring.
b. Aircraft top/bottom antenna indication for each UAT message to evaluate top and bottom antenna performance
c. Aircraft state data (Reception time, GPS position, pressure altitude, ground speed vector, heading, roll angle) for background information, scenario re-creation and specific investigations as necessary.

Analysis of the data logs collected in the trials showed that

1. Both the measured air-to-air and air-to-ground ranges matched closely the expectations from link budget calculations;
2. Passive range measurements were shown to achieve an accuracy of ~ 150 m.
3. Some unexpected performance variations were observed which were attributed to antenna placement and antenna gain variations on the aircraft

UAT trial interim results were presented by EEC staff to the TLAT. The EEC is continuing the analysis of the trial data and these are being used for validation of the TLAT UAT model as follows: Simulation scenarios are constructed matching the UAT station positions and aircraft tracks recorded in the trial sessions. These scenarios will be run with the TLAT UAT simulation model, appropriately adapted to the UAT trial equipment configuration. Receiver ADS-B performance will be analysed and compared with the measurements made in the trials.

[3] CAPSTONE equipment is considered as A0/A1 class (measured TX power was <= 30 W).
[4] LDPU radios were used in the development of the TLAT UAT receiver waveform model for simulations. CAPSTONE radios are of the same type as the UAT radio built into the LDPU.

K.1.3 VDL Mode4 Trial in Groningen, Netherlands, 30 Nov to 7 Dec 2000

These flight trials were organised by NLR under Eurocontrol sponsoring with the participation of the Swedish CAA, and ADSI Inc.. VDL Mode 4 operation was tested in the 136.975 MHz channel, which in Europe has been (temporarily?) dedicated to VDL Mode 2 but was not used at the time of the trials. The primary goals of the VDLMode 4 trials were:

1. Characterising performance of a/a and a/g VDLMode 4 operation in a "free" RF channel under various flight geometries.
2. Evaluating the efficiency of using antenna diversity for VDLMode 4 (previous trials had always used single antennas – the TLAT VDLMode4 System Description (Appendix E) recommends diversity).
3. Evaluating the impact of higher transmission powers on VDL Mode 4 performance (previous trials had used 5W transmitters).
4. Comparing the performance of EVR-200 VDL Mode 4 radios[5] with that of SAAB Celsius radios used in the 1999 trials
5. Recording data to support simulation model validation

Two project aircraft were used including a Fairchild Metroliner supplied by NLR and a Beech 200 supplied by the Swedish CAA. The Metroliner had also been used in the Frankfurt 1090 trial and the Paris UAT trial. Both project aircraft were equipped with two EVR-200 radios connected to top and bottom VHF antennas. Two different versions of the EVR-200 radios were used, one supplied by ADSI and the other by SCAA.

A ground VDL Mode 4 station was installed at Eelde airport in Groningen that served as base for the project aircraft. The ground station consisted of an EVR-200 radio and a standard vertical dipole VHF antenna.

There were in total two flight trial sessions (with both project aircraft participating) and two pre-trial calibration sessions (one per project aircraft). The first trial session used ADSI radios and the second SCAA ones. The following elements were recorded in the flight sessions:

a. VDL Mode 4 message reports from the project aircraft to generate statistics on reception probabilities as functions of range and geometry, and test (offline) passive range monitoring.

b. Aircraft top/bottom antenna indication for each VDL Mode 4 message to evaluate top and bottom antenna performance

c. Aircraft state data (Reception time, GPS position, pressure altitude, ground speed vector, heading, roll angle) for background information, scenario re-creation and specific investigations as necessary.

Analysis of the data logs collected in the trials showed that

- The use of 18W transmitters achieved a reception probability of more than 60% at 200 nmi
- For air-to-air scenario, top-mounted antenna appeared to be better for head-on aspects and bottom-mounted antenna appeared to be better for tail-on aspects.
- Aircraft equipped with top and bottom mounted antennas will experience good reception during turns relative to other aircraft
  - however deterministic transmissions from one antenna or the other led to airframe shadowing of the transmissions during half of each turn by each transmitting aircraft.

[5] EVR-200 radios were used for developing the TLAT VDL Mode 4 receiver waveform model

4. Alternating transmissions (top/bottom) would mitigate this issue and it is expected to lead to performance of 60% delivery probability (from one turning aircraft to another turning aircraft) at a range of 20 nmi.

5. Some unexpected performance variations were observed which were attributed to antenna placement and antenna gain variations on the aircraft

The TLAT received presentations of interim VDL Mode 4 trial results by Swedish CAA and ADSI staff. EEC and the other trial partners are continuing the analysis of the collected data. The EEC will use VDL Mode 4 trial data to validate the TLAT VDL Mode 4 simulation models as follows: Simulation scenarios will be constructed matching the VDL Mode 4 station positions and aircraft tracks as recorded in the trial sessions. These scenarios will be run with the TLAT simulation model (SPS with APL MER model and including the TLAT antenna gain model) appropriately adapted to the equipment configurations used in the trial. Receiver ADS-B performance will be analysed and compared with the measurements made in the trials.

K.2 Simulation results

A number of assumptions went into the simulation of each of the data link candidates. Some of these assumptions apply equally to all of the links. These have been enumerated in Section 4. Table K.2-1 below summarizes the location in the report for those assumptions which differ from link to link.

	UAT	**1090 Extended Squitter**	**VDL Mode 4**
Transmission Rate	See Appendix D	See Appendix C	See Appendix E
Transmit Power	See Appendix D	See Appendix C	See Appendix E
Receive Sensitivity	See Appendix D	See Appendix C	See Appendix E
Antenna Gain	See Appendix J	See Appendix J	See Appendix J (some results assume constant antenna gain)
Co-site Interference	See Table K.2-2 below.	See Table K.2-2 below.	Co-site transmissions from all channels
Receiver Performance Model	See Appendix I	See Appendix I (results for Core Europe 2015 used simplified receiver performance model not based on Appendix I data)	See Appendix I
FIS-B	See Appendix J	See Appendix J	See Appendix J
TIS-B	See Appendix J	See Appendix J	See Appendix J

Table K.2-1 Link Assumptions

Type	#/sec	Duration (microsecs)
DME	70	12
ATCRBS replies	~200	20
Mode S replies	~4-5	64
Mode S interrogations	~5	20
Whisper/shout interrogations	~80	25

Table K.2-2 Co-site Interference Sources for UAT and 1090

All links are subject to the constraint that they are assumed incapable of receiving an ADS-B message while transmitting an ADS-B message.

It should be noted that there is expected to be some variability in results from the simulations. This is a consequence of the data being derived from a limited statistical sample. The results shown for the update periods use the 95% point (as defined in the ADS-B MASPS), in order to sample the expected performance variations and increase the probability of accounting for most of the expected variability in scenarios. The 95% point for update times has been interpreted by the TLAT as meaning that 95% of aircraft at the given range are expected to achieve the update rate 95% of the time.

K.2.1 UAT Simulation Results

The UAT simulation results are depicted in the presentation slides included in Attachment 2 of Appendix K.

K.2.2 1090 MHz Extended Squitter Simulation Results

The 1090 MHz Extended Squitter simulation results are depicted in the presentation slides included in Attachments 2 and 3 of Appendix K.

For each of the considered scenarios, there are a number of graphs per scenario depicting:

- the message success rate versus the range
- the State vector update time versus range, and
- the TCP update time versus range.

There were two simulation tools utilised to characterise 1090 MHz Extended Squitter performance, the VOLPE-JHU and the DERA SIEM. The VOLPE-JHU simulation tool was used to generate results for the Los Angeles Basin 2020 scenario and the SIEM simulation tool was used for the Core Europe 2015 scenario. The Los Angeles Basin 2020 scenario was run using two interference environments. As expected, the performance of 1090 MHz Extended Squitter is highly dependent on the ATCRBS and Mode S interference rates that can be expected from ground interrogators and airborne interrogators such as TCAS. Two interference scenarios were chosen so that the performance sensitivity to interference rates could be measured. The two interference scenarios are referred to as the low interference and high interference environments. The low interference environment represents an ATCRBS rate approximately 75% of the current ATCRBS rate as measured in the current Los Angeles Basin environment. The high interference environment has an ATCRBS rate approximately 2 times the measured rate in the current Los Angeles Basin environment. The resultant ATCRBS interference rate produced by the simulation for the high interference environment is consistent with expected ATCRBS rates produced by an independent analytical model (see section K.2.2.3).

The LA 2020 scenario analysis included a number of assumptions:

- The ground interrogator environment will be comparable to the current environment, with the exception that two of the current ATCRBS interrogators will be converted to Mode S by 2020.
- The mix of aircraft will be 90% Mode S transponders and 10% ATCRBS transponder-based. All aircraft are augmented with Extended Squitter.
- The fraction of TCAS equipage in the aircraft population will remain at 60%.
- The Terra fix will be eliminated.
- Hybrid surveillance is assumed for TCAS interrogation rate reduction.
- All deployed systems are assumed to be MOPS compliant.

The Volpe-JHU simulation selected an A3-equipped victim receiver near the centre of the LA 2020 scenario at an altitude of 39000 ft. The receiver sensitivity was assumed to be –84 dBm. The antenna gain model described in Appendix J was implemented for the Volpe-JHU simulation. This was the same receiver selected for the simulations of the other two candidates.

The DERA SIEM simulation tool was utilised by Eurocontrol to produce results against the Core Europe 2015 scenario. To validate the model, a current Frankfurt, Germany scenario was run to compare produced interference rates against measured rates made in the Frankfurt measurements in May 2000. The ATCRBS and Mode S interference rates produced were compared against measurements made in the Frankfurt area. The results did not totally agree and the differences along with possible explanations are included in the Core Europe scenario results discussion below.

The DERA-SIEM simulation of Core Europe looked at two victim receivers, an A3-equipped aircraft at 30000 ft and an A0-equipped aircraft at 15000 ft. The receiver sensitivities were assumed to be –84 dBm for the A3 and –72 dBm for the A0. The antenna gain model described in Appendix J was implemented for the DERA-SIEM simulation.

There are three sections in the 1090 MHz Extended Squitter simulations. The first section is a set of slides which represent the Volpe-JHU simulation results and summaries. The second section is a set of slides, which describes the DERA SIEM simulation results and findings. The third section describes an independent validation of the scenario results for the LA Basin scenario.

K.2.2.1 Volpe/JHU

See Attachment 2 of Appendix K.

K.2.2.2 DERA/Eurocontrol

See Attachment 3 of Appendix K.

K.2.2.3 1090 MHz Extended Squitter Independent Sensitivity Analysis

K.2.2.3.1 Introduction

A separate ES analytical model was used as an independent check on the LA scenario simulation results and to examine the sensitivity of expected performance to possible differences in the interference environment. In this model, interference sources are characterised in terms of:

- The number of ground interrogators in view at an average altitude and their characteristics, i.e., ATCRBS (sliding window or monopulse) or Mode S.
- The aircraft distribution in range from the victim receiver and population characteristics, i.e. ATCRBS or Mode S transponder or TCAS equipage.

Aircraft antenna gain variations are modelled with a Gaussian distribution based on Lincoln Laboratory antenna pattern measurements. The ES receiver sensitivity response is an empirical fit to bench measurements. The message decoder uses a Poisson arrival model with a simplified amplitude dependent interference overlap decoder. The model outputs are normalised interference distributions and the expected probability of decoding ES messages as a function of source aircraft separation range.

K.2.2.3.2 Model Comparison with LA 1999 Flight Tests

The model is compared first with the data collected in the 1999 Los Angeles Basin flight tests. The radar measured aircraft distribution from Los Angeles Basin is extrapolated in Figure 1 to line of sight limits for the receiver at a flight test altitude of 17,500 feet. Based on interference source information gathered during the tests, the computed distribution of interference is shown in Figure 2 normalised to –84 dBm. Figure 2 is in excellent agreement with measured fruit rates given in the Los Angeles Basin 1999 Flight Test Report. Figure 3 shows the resulting probability of message decodes versus separation range. Again, these results are in close agreement with measured data. The lower boundary defined by the dash-dot line indicates MASPS required minimum level of performance. The effect of not including longer-range aircraft in the performance estimate is illustrated by truncating the Figure 1 distribution as shown in Figure 4. The resulting interference distribution shown in Figure 5 results in much longer-range performance as shown in Figure 6. Longer-range capability is achieved in this case since the weaker long-range messages are competing with lower rates of lower level interference.

K.2.2.3.3 LA 2020 Performance Sensitivity Examples

Sensitivity of ES performance to variations in future conditions was examined for three assumed scenarios:

- TLAT Los Angeles Basin 2020,
- TLAT Los Angeles Basin 2020 scenario with truncated traffic distributions, and
- TLAT Lax 2020 scenario with all Mode S ground interrogators and Mode S aircraft transponder equipage

a. TLAT Los Angeles Basin 2020 Scenario

The increased traffic level for the Los Angeles Basin 2020 scenario is shown in Figure 7. In this case all aircraft are assumed to be Mode S equipped with an average ES rate of 6 messages per second. Sixty percent of the population is TCAS equipped and hybrid surveillance is assumed to reduce the average TCAS interrogation rate to one per 10 seconds. The ground interrogator population (25% are Mode S) is the same as today except the Terra fix is removed from Mode S interrogators. The resulting interference rates relative to –84 dBm are shown in Figure 8. Expected probability of Extended Squitter decodes versus range is given in Figure 9. The mean operational range is 20 nautical miles in this case.

b. TLAT Scenarios with Truncated Traffic

All assumptions are the same as the TLAT Los Angeles Basin 2020 scenario in this case except the traffic is truncated in range as previously described. The associated truncated interference rates are given in Figure 10. In this case, as shown in Figure 11, this has little effect on the resulting probability of decode. This is due to the high residual interference rate even though the low-level rate is truncated.

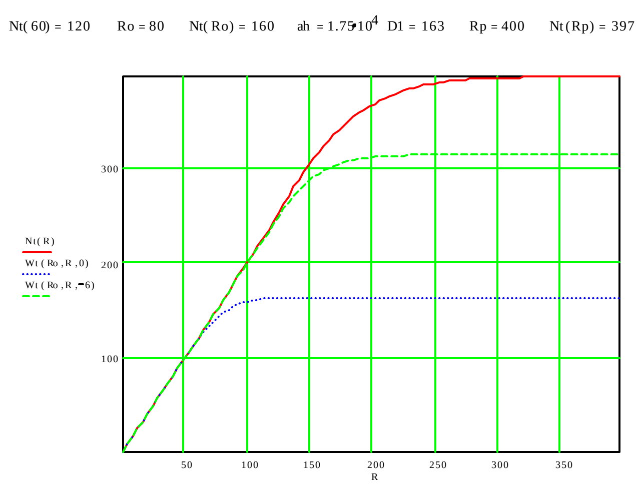
c. All Mode S Ground Interrogators and Mode S Aircraft Transponder Equippage

The traffic distribution of Figure 7 is again employed except in this case all ground interrogators are Mode S as well as the all Mode S traffic assumption. Resulting interference is now only standard Mode S replies (no ATCRBS interference) as shown in Figure 12. Some improvement in performance is achieved in this case as illustrated in Figure 13 where the indicated range is about 30 nautical miles.

K.2.2.3.4 Summary

Agreement between the analytical model and 1999 Los Angeles Basin measurements was used as a baseline for comparison of the expected sensitivity of ES capability to postulated future operational environments. Although performance is sensitive to these assumptions for current traffic levels. Future TLAT assumed traffic levels produce such high associated interference levels that variations around these assumed future conditions only have a modest effect on capability.

Realistic Traffic Distribution for
LA'99 Flight Tests (solid line)



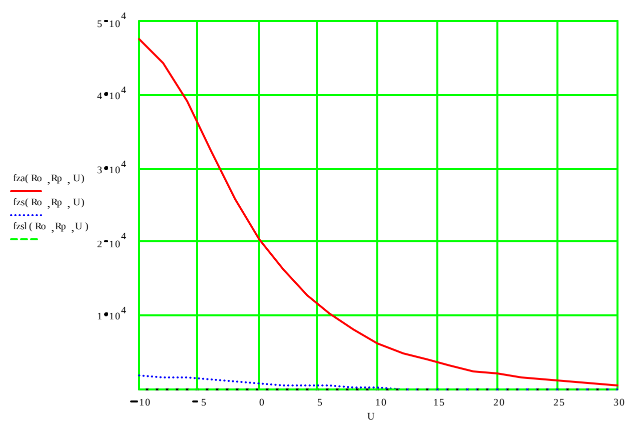
3/08/01 Sqtr_Sensvty

Figure 1: Number of a/c versus range (top curve), number of a/c with signal above MTL-6dB (mid curve), number of a/c above MTL (bottom curve)

Mode-A/C and Mode-S Fruit Distributions Normalized to -84 dBm for Realistic Traffic Distribution

$N = 397$ $ah = 1.75 \cdot 10^{4}$ $Rp = 400$ $fs = 0.45$ $ft = 0.45$ $Ntc = 24$ $ks = 1$ $ss = 1$ $SA = 0$

$M = 28$ $g \cdot a = 0.25$ $\mu u = 0$ $\sigma u = 2$ $Ro = 80$ $Ra = 80$ $ia = 151.8$ $is = 10.2$ $zsl = 4.5 \cdot 10^{-3}$



3/08/01 Sqtr_Sensvty

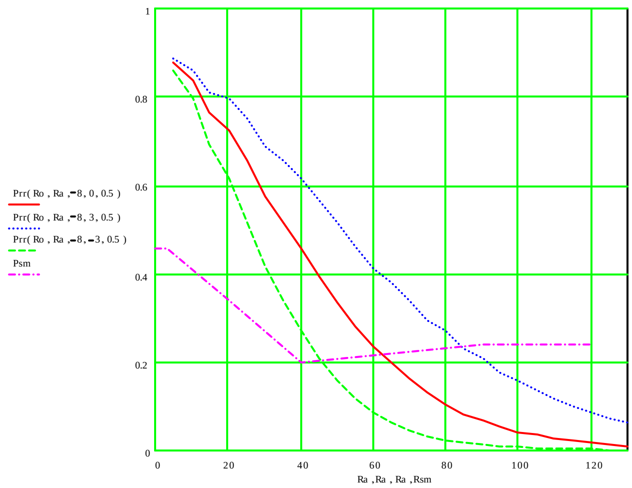
Figure2: Fruit replies/sec versus amplitude relative to –84 dBm; ATCRBS (top curve), Mode S (bottom curve)

Resulting Squitter Decode Probability vs Range for LA'99 Realistic Traffic Distribution (mean & +/- 3 dB)

$Ro = 80 \quad \mu = 0 \quad \sigma = 0.5 \quad MTL - T = 8 \quad Pm(0, T) = 0.9 \quad Nt(60) = 120 \quad ah = 1.75 \cdot 10^4$

$\sigma c = 1 \quad \delta 50 = 0 \quad \delta 05 = 1.65 \quad \delta 95 = -1.65 \quad \eta = 0.9$

$\mu u = 0 \quad \sigma u = 2 \quad fza(Ro, Rp, 0) = 2.049 \cdot 10^4 \quad fzs(Ro, Rp, 0) = 829.195 \quad \gamma a = 3 \quad \gamma s = 6$

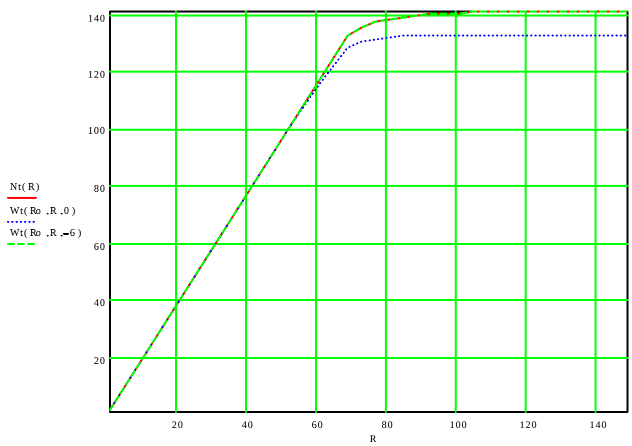


3/08/01 Sqtr_Sensvty

Figure 3: Probability of message decode versus range (nm): mean population (middle curve), upper and lower limits are mean +/- 3 dB, minimum required probability of decode (lower line)

Truncated Traffic Distribution for LA'99 Flight Tests

Nt(60) = 116 Ro = 80 Nt(Ro) = 139 ah = 8•10^3 D1 = 110 Rp = 150 Nt(Rp) = 141



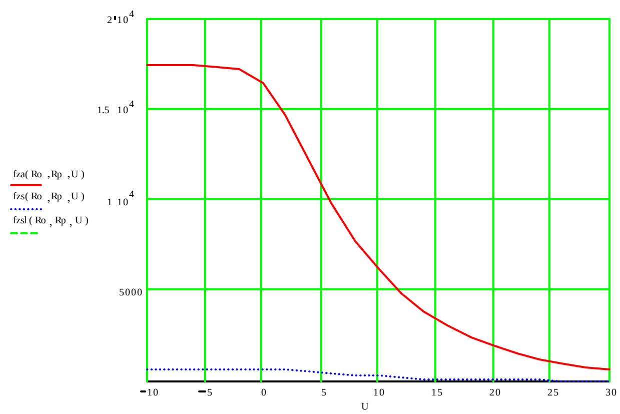
3/08/01 Sqtr_Sensvty

Figure 4: Number of a/c versus range

Mode-A/C and Mode-S Normalized Fruit Distribution for Truncated Traffic Distribution

$N = 141$ $ah = 8 \cdot 10^3$ $Rp = 150$ $fs = 0.45$ $ft = 0.45$ $Ntc = 23$ $ks = 1$ $ss = 1$ $SA = 0$

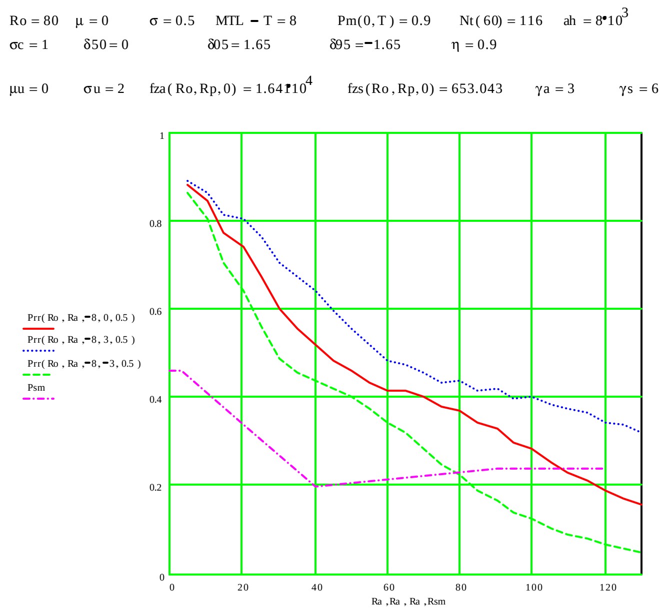
$M = 28$ $g \cdot a = 0.25$ $\mu u = 0$ $\sigma u = 2$ $Ro = 80$ $Ra = 80$ $ia = 149.5$ $is = 9.9$ $zsl = 4.5 \cdot 10^{-3}$



3/08/01 Sqtr_Sensvty

Figure 5: Fruit replies/sec versus the normalised signal level; ATCRBS (top curve), Mode S (bottom curve)

Resulting Squitter Decode Probability vs Range for LA'99 Truncated Traffic Distribution

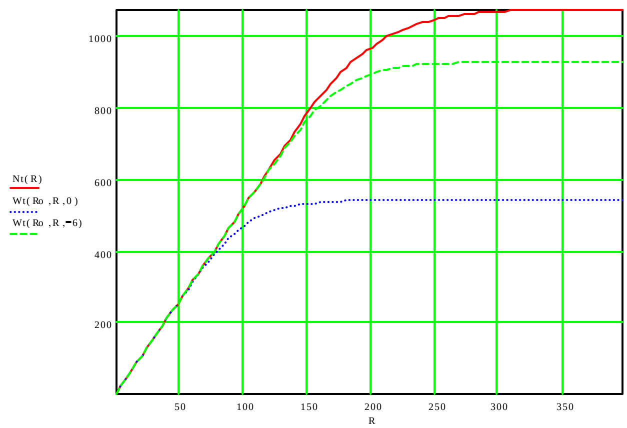


3/08/01 Sqtr_Sensvty

Figure 6: Probability of message decode versus range (nm): mean population (middle curve), upper and lower limits are mean +/- 3 dB, minimum required probability of decode (lower line)

TLAT 2020 LA Traffic Distribution with LOS Constraint (Scenario 1)

Nt(50) = 262 Ro = 100 Nt(150) = 785 ah = $3 \cdot 10^4$ D1 = 213 Rp = 400 Nt(Rp) = 1080



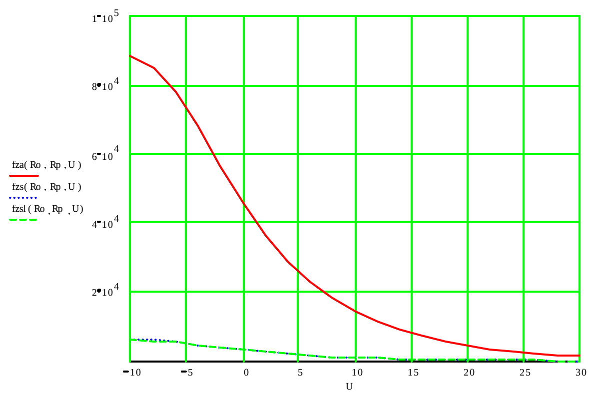
3/08/01 Sqtr_Sensvty

Figure 7: Number of a/c versus range (top curve), number of a/c with signal above MTL-6dB (mid curve), number of a/c above MTL (bottom curve)

Normalized Fruit Distributions for
TLAT 2020 LA Traffic: all Mode-S
aircraft, current I/Rs, & hybrid TCAS

N = 1080 ah = 3·10^4 Rp = 400 fs = 1 ft = 0.6 Ntc = 85 ks = 0.1 ss = 1 SA = 1

M = 28 g·a = 0.25 μu = 0 σu = 2.5 Ro = 100 Ra = 90 ia = 171 is = 5.1 zsl = 6



3/08/01 Sqtr_Sensvty

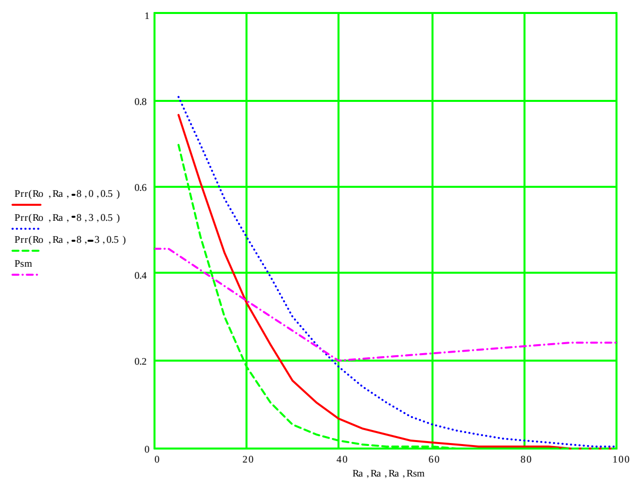
Figure 8: Fruit replies/sec versus amplitude relative to –84 dBm;
ATCRBS (top curve), Mode S (bottom curve)

Resulting Squitter Decode Probability vs Range for LA 2020 Scenario 1 (mean & +/- 3 dB)

$Ro = 100$ $\mu = 0$ $\sigma = 0.5$ $MTL - T = 8$ $Pm(0, T) = 0.9$ $Nt(60) = 314$ $ah = 3 \cdot 10^4$

$\sigma c = 1$ $\delta 50 = 0$ $\delta 05 = 1.65$ $\delta 95 = -1.65$ $\eta = 0.9$

$\mu u = 0$ $\sigma u = 2.5$ $fza(Ro, Rp, 0) = 4.562 \cdot 10^4$ $fzs(Ro, Rp, 0) = 3.289 \cdot 10^3$ $\gamma a = 3$ $\gamma s = 6$

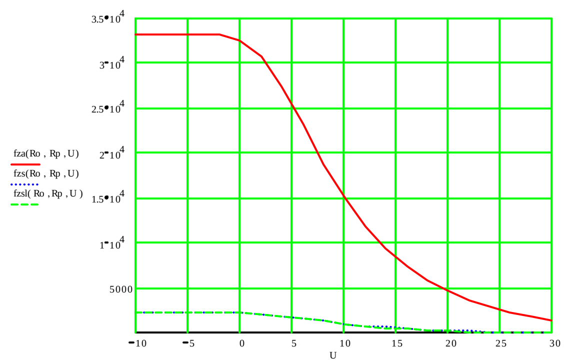


3/08/01 Sqtr_Sensvty

Figure 9: Probability of message decode versus range (nm): mean population (middle curve), upper and lower limits are mean +/- 3 dB, minimum required probability of decode (lower line)

Normalized Fruit Distributions for
Truncated 2020 LA Traffic:
all Mode-S aircraft, current I/Rs, &
hybrid TCAS

N = 396 ah = $8 \cdot 10^3$ Rp = 150 fs = 1 ft = 0.6 Ntc = 87 ks = 0.1 ss = 1 SA = 1
M = 28 g·a = 0.25 μu = 0 σu = 2.5 Ro = 100 Ra = 90 ia = 171 is = 5.1 zsl = 6



3/08/01 Sqtr_Sensvty

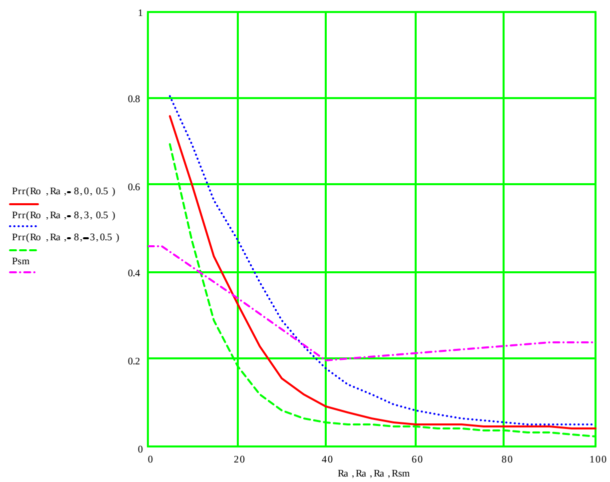
Figure 10: Fruit replies/sec versus the normalised signal level;
ATCRBS (top curve), Mode S (bottom curve)

Resulting Squitter Decode Probability vs Range for LA 2020 Scenario 2 (mean & +/- 3 dB)

$Ro = 100$ $\mu = 0$ $\sigma = 0.5$ $MTL - T = 8$ $Pm(0, T) = 0.9$ $Nt(60) = 324$ $ah = 8 \cdot 10^{3}$

$\sigma c = 1$ $\delta 50 = 0$ $\delta 05 = 1.65$ $\delta 95 = -1.65$ $\eta = 0.9$

$\mu u = 0$ $\sigma u = 2.5$ $fza(Ro, Rp, 0) = 3.247 \cdot 10^{4}$ $fzs(Ro, Rp, 0) = 2.373 \cdot 10^{3}$ $\gamma a = 3$ $\gamma s = 6$

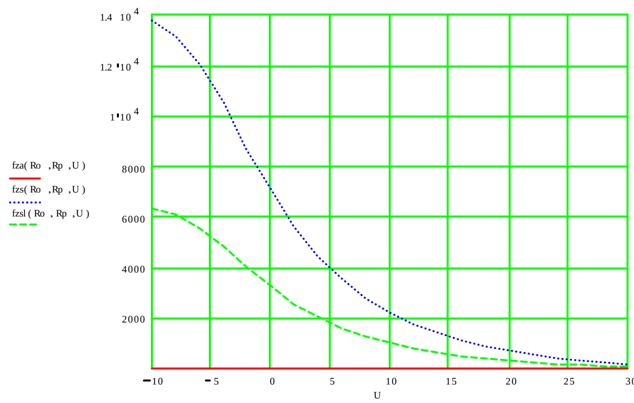


3/08/01 Sqtr_Sensvty

Figure 11: Probability of message decode versus range (nm): mean population (middle curve), upper and lower limits are mean +/- 3 dB, minimum required probability of decode (lower line)

Normalized Fruit Distributions for TLAT 2020 LA Traffic: all Mode-S aircraft, all Mode-S I/Rs, & hybrid TCAS

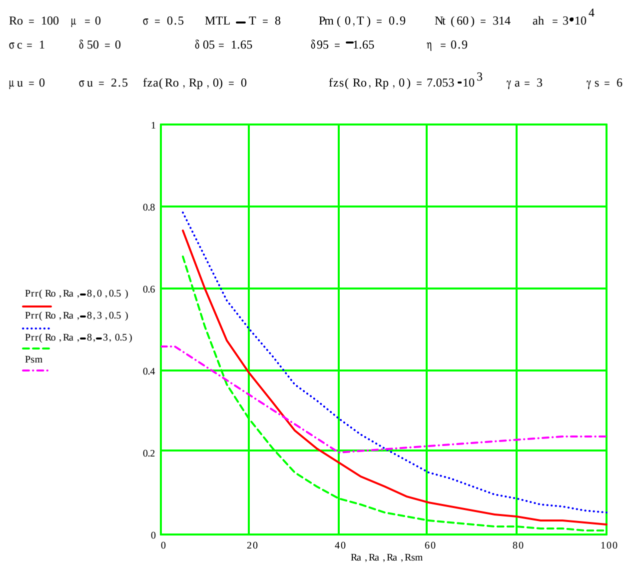
N = 1080 ah = 3·10^4 Rp = 400 fs = 1 ft = 0.6 Ntc = 85 ks = 0.1 ss = 1 SA = 1
M = 28 g a = 1 μu = 0 σu = 2.5 Ro = 100 Ra = 90 ia = 108 is = 12 zsl = 6



3/08/01 Sqtr_Sensvty

Figure 12: Fruit replies/sec versus MTL normalised signal level; Mode S replies ((top curve), ES messages (bottom curve)

Resulting Squitter Decode Probability
vs Range for LA 2020 Scenario 3
(mean & +/- 3 dB)



3/08/01 Sqtr_Sensvty

Figure 13: Probability of message decode versus range (nm): mean population (middle curve), upper and lower limits are mean +/- 3 dB, minimum required probability of decode (lower line)

K.2.3 VDL Mode 4 Simulation Results

Two versions of SPS were used to characterize VDL Mode 4 performance, the JHU version and the Eurocontrol one. The JHU simulation tool was used to generate results for the Los Angeles Basin 2020, Core Europe 2015, and the low density scenarios, and the Eurocontrol simulation tool was used for the Core Europe 2015 scenario. In both cases the methodology outlined in Section 4 was used. There were differences in the way that each version implemented the various assumptions, and these differences are outlined below.

The JHU simulation selected an A3-equipped victim transceiver near the center of the LA 2020 scenario at an altitude of 39000 ft., and another A3-equipped transceiver at 37000 ft for the Core Europe 2015 scenario. The receiver sensitivities were both assumed to be –93 dBm. The antenna gain model described in Appendix J was implemented for the simulation. These were the same receivers selected for the simulations of the other two candidates.

The Eurocontrol simulation selected an A3-equipped victim transceiver located at the center of the Core Europe 2015 scenario at altitudes ranging from 60ft to 30000ft. Performance was also evaluated for all receivers within x nmi of the scenario center (x ranging from 0 to 100 nmi). Receiver sensitivities were assumed to be –93 dBm. The antenna gain model described in Appendix J was implemented only for some runs.

There are two sections in the VDL Mode 4 simulations results. The first section is a set of slides, which represent the Eurocontrol EEC simulation results. The second section is a set of slides, which describes the JHU simulation results.

K.2.3.1 EEC Simulations

The results of EEC simulations are depicted in the presentation slides contained in Attachment 4 of Appendix K. EEC focused on the Core Europe 2015 scenario. The assumptions made and the analysis methods applied are explained in the notes accompanying the slides.

K.2.3.2 JHU Simulations

The results of JHU/APL VDL Mode 4 simulations are depicted in the presentation slides included in Attachment 5 of Appendix K.

The major assumptions used in the simulations are shown above. For each of the considered scenarios, there are a number of graphs per scenario depicting:

- the message success rate versus the range
- the State vector update time versus range, and
- the TCP update time versus range.

The high density scenarios (Los Angeles Basin 2020 and Core Europe 2015) contain four separate channels each. A separate run was made for each individual channel: two Global Signaling Channels (GSC1 & 2) and two regional signaling channels (RSC1 & 2). The victim receiver was present in all channels, but was present only as a passive listener in RSC2, since an aircraft in the region only transmits on one of the regional channels, but listens to both. In this manner, all of the aircraft surrounding the victim were analyzed for performance.

For each channel run, the first 15 frames are discarded, since the system may require this much time to reach a stable state. The remaining data (frames 16-30) are then analyzed for system performance.

According to the system description, each A2/A3 aircraft transmits a two-slot message once a minute on one of the global signaling channel. Since the simulation is unable to handle a multi-slot message, for the APL simulation the two-slot message was simulated as two single-slot messages. After the simulation run was completed, the two single messages were combined into a two-slot message. This two-slot message contains all four TCPs as well as the ID and state vector information.

Ground station transmissions (FIS-B and Directory of Service/GNSS messages) were handled in the APL simulation by reducing the number of slots available to the aircraft for their transmissions. This was done in accordance with estimates provided by the subject matter experts.

The analysis of the APL results revealed a problem with the SPS dithering of individual channels. The subject matter experts examined the extent of dithering allowed and determined that it was in excess of that allowed by the SARPS. Several subsequent test runs of the low density scenario, without dithering and with perfect reception, revealed that the dithering was actually causing the VDL Mode 4 results to change from acceptable to unacceptable with regard to the MASPS criteria. This situation was deemed to be objectionable. Therefore, in interpreting the results, the TLAT accounted for the unacceptably large dither effects. However, the discovery of this phenomenon revealed a potential weakness in VDL Mode 4 which can be avoided by maintaining the limitations on the dithering. An analytical examination of clear slot selection sensitivity to the dither interval is included in Appendix M.2.

Appendix L: Multi-Link Considerations

1.0 Introduction

Until recently, ADS-B efforts have focused on single-link operations. Each of the links has advantages, some differing. Various user groups and ATC service providers have strong reasons for selecting a specific link. Due to these reasons an initiative was started to assess the technical viability and the cost practicality of a multi-link solution. The concept of using two or more ADS-B links to achieve desired interoperability with either other aircraft or with available ground systems is the general intent of multi-link ADS-B systems.

The phrase multi-link has evolved to three different definitions:

1) Different ATC service providers, based on their perceived benefits, require different links in differing airspace environments. Avionics to support this need would be similar to a multi-mode radio.
2) Different user groups, based on their perceived benefits, choose different links for simultaneous operation in common airspace. Interoperability between groups may be provided in this case by a ground-based, cross-linked relay system or with some level of dual avionics equipage by at least one user group.
3) Users determine that their needs require the complementary capability of dual links. As an example, one link supports long-range needs with the other providing short-range capability.

If a multi-link solution is chosen, requirements for multi-link operations must be defined. This appendix discusses technical aspects of the use of multiple ADS-B situational awareness links for different aircraft types and in different airspace types. Requirements deriving from these technical aspects have not been viewed within any formal standards setting organization.

For the purposes of this appendix (using the second definition referenced above), multi-link ADS-B is considered to be the simultaneous use of two or more ADS-B/situational awareness links to facilitate exchange of ADS-B traffic information between airborne ADS-B users (either directly or through a ground-based cross-linked relay system), and between airborne ADS-B users and ground-based air traffic management facilities. However, much of the discussion applies to the more general case of multi-mode multi-link systems (the first definition referenced above).

The FAA and MITRE/CAASD are currently conducting a survey to explore the costs and technical issues associated with multi-link ADS-B. The survey's purpose is to elicit vendor/stakeholder comments necessary to develop a more quantitative understanding of the incremental costs and technical issues associated with implementation of multi-link ADS-B avionics. The survey does not specifically seek to address either optimization of communications, navigation, and surveillance avionics architectures or potential advantages or issues related to link diversity.

2.0 ADS-B Multi-link: Conceptual Description, Interoperability, and Ground System Compatibility

2.1 General

Two of the multi-link ADS-B schemes examined appear to be feasible within the current airspace structures in use – a ground-based cross-link relay (Ground Gateway) and a multi-link airborne system (Multi-Link Airborne). The major differences between the concepts center on degree of autonomy and location of additional components (e.g., additional link receiver/transmitter, etc.). Either multi-link concept provides multi-link functionality; however, this functionality may be limited to specific geographic areas for gateway or to specific users due to airborne equipage. Either scheme may be augmented by TIS-B to provide additional interoperability between equipped and non-equipped aircraft.

2.2 Ground Gateway ADS-B Systems

Multi-link ADS-B as implemented through use of a ground gateway or cross-link relay may provide multi-link ADS-B interoperability without the requirement for users to equip with a multi-link airborne unit – though at the cost of limiting interoperability to specific geographic areas.

While requiring no additional aircraft equipage other than either Link-X or Link-Y (with X and Y representing one of the three potential links), Ground Gateway does require a ground station to be within range of each participating aircraft. Each ground station includes a Link-X and Link-Y receiver, cross-link processor, and Link X and Link-Y transmitter as illustrated in Figure L-1 below.

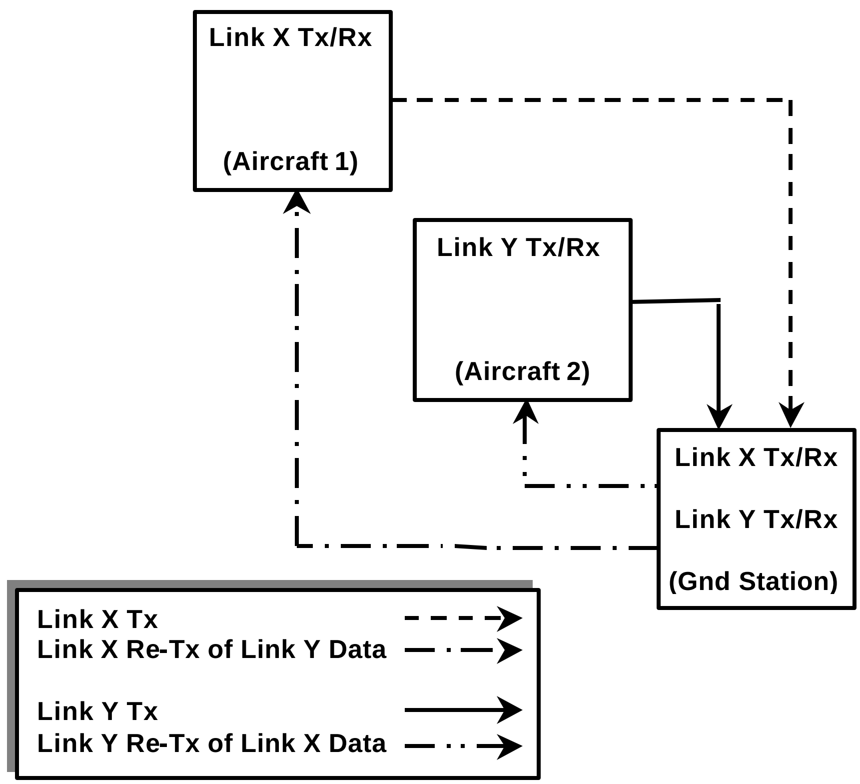


Figure L-1: Interoperability Between Link X Equipped Aircraft and Link Y Equipped Aircraft via Cross-Link Relay (Ground Gateway)

The following characteristics describe multi-link functionality for a Ground Gateway-based system:

- Ground Gateway multi-link architectures depend on ground infrastructure to share information between two dissimilarly-equipped ADS-B aircraft within the service volume of the gateway.

- Ground Gateway coverage is based on establishing ground sites to facilitate the cross-linking of data between dissimilarly equipped ADS-B aircraft.

- Interoperability between dissimilarly equipped ADS-B aircraft would be limited to the volumes served by ground gateways.

- Ground gateway may increase overall time for messages to move between dissimilarly equipped ADS-B aircraft.

- Some additional cost, as well as increased ground facility space, processing, and power requirements, may be expected over a single-link ADS-B baseline.

The Ground Gateway concept is separate and distinct from TIS-B (Traffic Information Service – Broadcast) in that it does not depend on radar to detect and facilitate uplinking of traffic information – the Ground Gateway is simply a cross-linked relay, and may be sited in areas where radars are not feasible.

The configuration of the Ground Gateway would allow the facility to be used for other ADS-B and traffic awareness purposes. Where radar data is available, the presence of transmitter capability for two or more ADS-B links at the Ground Gateway site would allow addition of TIS-B messages to the cross-linked stream. Monitoring of ADS-B messages received by the Ground Gateway would also allow this data to be used to support ADS-B air-ground applications

2.3 Multi-Link Airborne ADS-B Systems

2.3.1 Description and Characteristics of Multi-Link Airborne Systems

Multi-Link Airborne equipage of some or all aircraft sharing airspace areas would require some subset of aircraft population to equip with some combination of the baseline link and the alternative link. For this discussion, the baseline link is considered to be 1090 MHz Extended Squitter, and the alternative links UAT or VDL Mode 4.

The characteristics of a Multi-Link Airborne scheme for multi-link ADS-B are:

- Autonomy from ground-based infrastructure for air-to-air applications.

- Some additional cost, as well as some probability of increase in space, weight, and power requirements for alternative link installation in aircraft.

- Some degree of additional complexity for integration and certification of alternative link hardware and software.

- Autonomous airborne operation may also increase ground costs, where ground sites are equipped with both Link X and Link Y receiver at ground sites. However, where a single link ground infrastructure is built around the Link Y link common to all users, Link X ground infrastructure may be eliminated to reduce costs relative to a baseline single-link system.

The schematic below (Figure L-2) illustrates the basic connectivity and functionality of an autonomous multi-link airborne architecture. Link X represents the baseline link, while Link Y designates an alternative link. Aircraft 1 is equipped with a multi-link airborne system (Link X plus Link Y), while Aircraft 2 carries only the alternative Link (Link Y). Note that as a general objective, the proposed notional systems support full diversity reception and switched top/bottom antenna transmission for installed links for IFR-equipped aircraft; for the sake of clarity, reception diversity and multiple antennas for transmissions are not depicted.

Aircraft 1 transmits and receives on Link X as well as transmits and/or receives on Link Y. Aircraft 2 transmits and receives only on Link Y; the aircraft share Link Y as a common link, thus achieving interoperability where ADS-B applications have been implemented.

The ground site may be configured to receive Link-X and Link-Y or Link-Y only. Addition of a TIS-B component may also result in transmit capability on both Link-X and Link-Y or on Link-Y-only. While application of a multi-link airborne architecture adds some elements of dual link equipage for one or more user groups, it would also likely require some changes at ground sites to provide information for certain ADS-B applications.

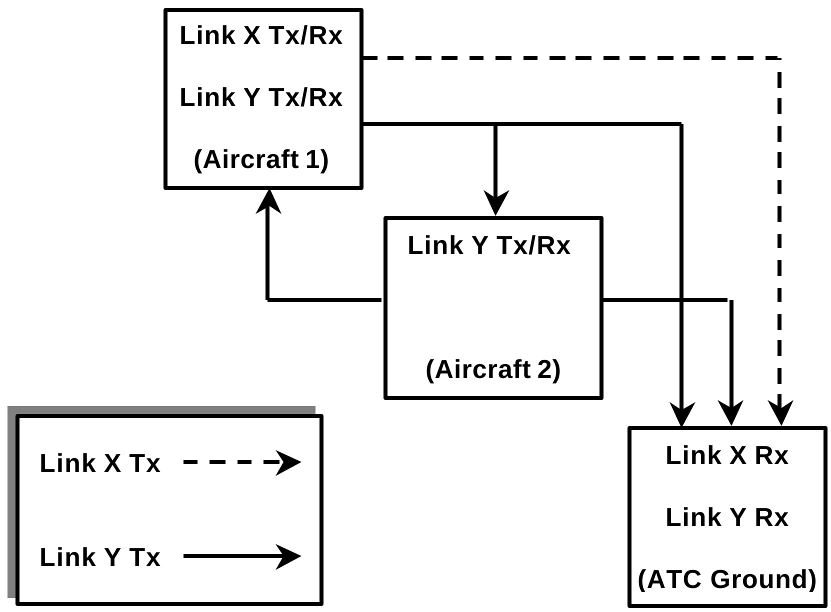


Figure L-2: Autonomous Interoperability Between Link X and Link Y Equipped Aircraft Provided by Common Link Y (Dual Link Ground Site)

2.3.2 Potential Airborne Multi-Link Configurations

The configurations of airborne multiple link ADS-B of interest are tabulated in Table L-1 below. In general, these configurations may be grouped according to combinations of Extended Squitter and another link, as well as specific transmit and receive capabilities and other surveillance or situational awareness capabilities. TCAS equipage, different platforms, and incremental cost constraints are the primary distinctions between air carrier and general aviation classes. Military aircraft are not specifically addressed but should generally fall into similar classes. In the following tables the phrase squitter means 1090 MHz Extended Squitter and the phrase VDL4 means VDL Mode 4.

Table L-1: Baseline and Multi-Link ADS-B Configurations

		Avionics Functionality								
	Config	TCAS	Mode A/C	Squitter		UAT		VDL4		Remarks
				Tx	Rx	Tx	Rx	Tx	Rx	
Baseline	Air Carrier	X		X	X					Designated baseline for costing purposes only
Baseline	GA		X	X	X					Designated baseline for costing purposes only
Air Carrier	1	X		X	X	X	X			Adds UAT transceiver to Air Carrier Baseline
Air Carrier	2	X		X	X		X			Adds UAT receiver to Air Carrier Baseline
Air Carrier	3	X		X	X	X				Adds UAT transmitter to Air Carrier Baseline
GA	4		X			X	X			Replaces GA Baseline Squitter with UAT
GA	5		X	X	X	X	X			Adds UAT transceiver to GA Baseline
GA	6		X		X	X	X			Adds Squitter receive-only capability to UAT transceiver
GA	7		X	X		X	X			Adds Squitter transmit-only capability to UAT transceiver
Air Carrier	8	X		X	X			X	X	Adds VDL4 transceiver to Air Carrier Baseline
Air Carrier	9	X		X	X				X	Adds VDL4 receiver to Air Carrier Baseline
Air Carrier	10	X		X	X			X		Adds VDL4 transmitter to Air Carrier Baseline
GA	11		X					X	X	Replaces GA Baseline Squitter with VDL4
GA	12		X	X	X			X	X	Adds VDL4 transceiver to GA Baseline
GA	13		X		X			X	X	Adds Squitter receive-only capability to VDL4 transceiver
GA	14		X	X				X	X	Adds Squitter transmit-only capability to VDL4 transceiver
Air Carrier	15	X		X	X	X	X	X	X	Includes transmit and receive capability for all three candidate ADS-B links

2.3.3 Airborne Multi-Link ADS-B Interoperability

The three links examined by the TLAT may be combined in terms of potential interactions to facilitate exchange of traffic awareness information. Tables L-2 and L-3 catalog the interoperability of various combinations of the seven Extended Squitter/UAT and seven Extended Squitter/VDL Mode 4 configurations tabulated in Table L-1 above.

The shaded areas of the two tables indicate air carrier-to-air carrier or GA-to-GA interoperability between various configurations of ADS-B links. The un-shaded areas of the matrix cover mixed-type operations, e.g., air carrier-to-GA or GA-to-air carrier. The entries in each matrix reflect the interoperability channel (TCAS, Extended Squitter, UAT, or VDL Mode 4) over which the receiving aircraft receives traffic information. Where the aircraft lack interoperability, a dashed line is used to indicate that fact.

To use the interoperability tables, select a transmitting aircraft configuration and a receiving aircraft configuration from the table. Note that the interoperability cell of the table (intersection of transmitting and receiving aircraft row and column) indicates the link or system on which the receiving aircraft will receive traffic information from the transmitting aircraft. An example follows.

> Example: For Aircraft A (Configuration 1) and Aircraft B (Configuration 4), Aircraft A (receiving aircraft) receives traffic information concerning Aircraft B (transmitting aircraft) via TCAS and UAT, while Aircraft B (receiving aircraft) receives traffic information concerning Aircraft A (transmitting aircraft) via UAT.

Entries in the Aircraft Configuration section of the tables indicate functionality, rather than any specific packaging or physical configuration of avionics systems. In the case of air carrier aircraft, Mode S transponder capability is assumed as an element of the TCAS system, while GA aircraft are assumed to be equipped with ATCRBS transponders, and annotated as Mode A/C-equipped.

Note that for all air carrier configurations, TCAS provides a method to alert and resolve traffic conflicts independent of ADS-B; in other words, the air carrier aircraft sees all other aircraft of Tables L-2 and L-3 via TCAS independent of their ADS-B configuration.

Interoperability for triple-link-equipped aircraft (configuration 15 from Table L-1) is not indicated; the assumption is that that the rationale for triple-link equipage would be to provide full interoperability in any ground or air environment.

Table L-2: Squitter/UAT Interoperability Matrix

			Receiving Air Carrier Aircraft				Receiving GA Aircraft				
		Receiving Aircraft Configuration	**Air Carrier Baseline**	**1**	**2**	**3**	**GA Baseline**	**4**	**5**	**6**	**7**
	Transmitting Aircraft Configuration		TCAS Squitter Tx/Rx	TCAS Squitter Tx/Rx UAT Tx/Rx	TCAS Squitter Tx/Rx UAT Rx	TCAS Squitter Tx/Rx UAT Tx	Mode A/C Squitter Tx/Rx	Mode A/C UAT Tx/Rx	Mode A/C Squitter Tx/Rx UAT Tx/Rx	Mode A/C Squitter Rx UAT Tx/Rx	Mode A/C Squitter Tx UAT Tx/Rx
Transmitting Air Carrier Aircraft	**Air Carrier Baseline**	-TCAS -Squitter Tx/Rx	TCAS Squitter	TCAS Squitter	TCAS Squitter	TCAS Squitter	Squitter	_ _ _ _	Squitter	Squitter	_ _ _ _
	1	-TCAS -Squitter Tx/Rx -UAT Tx/Rx	TCAS Squitter	TCAS Squitter UAT	TCAS Squitter UAT	TCAS Squitter	Squitter	UAT	Squitter UAT	Squitter UAT	UAT
	2	-TCAS -Squitter Tx/Rx -UAT Rx	TCAS Squitter	TCAS Squitter	TCAS Squitter	TCAS Squitter	Squitter	_ _ _ _	Squitter	Squitter	_ _ _ _
	3	-TCAS -Squitter Tx/Rx -UAT Tx	TCAS Squitter	TCAS Squitter UAT	TCAS Squitter UAT	TCAS Squitter	Squitter	UAT	Squitter UAT	Squitter UAT	UAT
Transmitting GA Aircraft	**GA Baseline**	-Mode A/C -Squitter Tx/Rx	TCAS Squitter	TCAS Squitter	TCAS Squitter	TCAS Squitter	Squitter	_ _ _ _	Squitter	Squitter	_ _ _ _
	4	-Mode A/C -UAT Tx/Rx	TCAS	TCAS UAT	TCAS UAT	TCAS	_ _ _ _	UAT	UAT	UAT	UAT
	5	-Mode A/C -Squitter Tx/Rx -UAT Tx/Rx	TCAS Squitter	TCAS Squitter UAT	TCAS Squitter UAT	TCAS Squitter	Squitter	UAT	Squitter UAT	Squitter UAT	UAT
	6	-Mode A/C -Squitter Rx -UAT Tx/Rx	TCAS	TCAS UAT	TCAS UAT	TCAS	_ _ _ _	UAT	UAT	UAT	UAT
	7	-Mode A/C -Squitter Tx -UAT Tx/Rx	TCAS Squitter	TCAS Squitter UAT	TCAS Squitter UAT	TCAS Squitter	Squitter	UAT	Squitter UAT	Squitter UAT	UAT

Table L-3: Squitter/VDL4 Interoperability Matrix

			Receiving Air Carrier Aircraft				Receiving GA Aircraft				
	Receiving Aircraft Configuration		**Air Carrier Base-line**	**8**	**9**	**10**	**GA Base-line**	**11**	**12**	**13**	**14**
	Transmitting Aircraft Configuration		TCAS Squitter Tx/Rx	TCAS Squitter Tx/Rx VDL4 Tx/Rx	TCAS Squitter Tx/Rx VDL4 Rx	TCAS Squitter Tx/Rx VDL4 Tx	Mode A/C Squitter Tx/Rx	Mode A/C VDL4 Tx/Rx	Mode A/C Squitter Tx/Rx VDL4 Tx/Rx	Mode A/C Squitter Rx VDL4 Tx/Rx	Mode A/C Squitter Tx VDL4 Tx/Rx
Transmitting Air Carrier Aircraft	**Air Carrier Baseline**	-TCAS -Squitter Tx/Rx	TCAS Squitter	TCAS Squitter	TCAS Squitter	TCAS Squitter	Squitter	_ _ _ _	Squitter	Squitter	_ _ _ _
	8	-TCAS -Squitter Tx/Rx -VDL4 Tx/Rx	TCAS Squitter	TCAS Squitter VDL4	TCAS Squitter VDL4	TCAS Squitter	Squitter	VDL4	Squitter VDL4	Squitter VDL4	VDL4
	9	-TCAS -Squitter Tx/Rx -VDL4 Rx	TCAS Squitter	TCAS Squitter	TCAS Squitter	TCAS Squitter	Squitter	_ _ _ _	Squitter	Squitter	_ _ _ _
	10	-TCAS -Squitter Tx/Rx -VDL4 Tx	TCAS Squitter	TCAS Squitter VDL4	TCAS Squitter VDL4	TCAS Squitter	Squitter	VDL4	Squitter VDL4	Squitter VDL4	VDL4
Transmitting GA Aircraft	**GA Baseline**	-Mode A/C -Squitter Tx/Rx	TCAS Squitter	TCAS Squitter	TCAS Squitter	TCAS Squitter	Squitter	_ _ _ _	Squitter	Squitter	_ _ _ _
	11	-Mode A/C -VDL4 Tx/Rx	TCAS	TCAS VDL4	TCAS VDL4	TCAS	_ _ _ _	VDL4	VDL4	VDL4	VDL4
	12	-Mode A/C -Squitter Tx/Rx -VDL4 Tx/Rx	TCAS Squitter	TCAS Squitter VDL4	TCAS Squitter VDL4	TCAS Squitter	Squitter	VDL4	Squitter VDL4	Squitter VDL4	VDL4
	13	-Mode A/C -Squitter Rx -VDL4 Tx/Rx	TCAS	TCAS VDL4	TCAS VDL4	TCAS	_ _ _ _	VDL4	VDL4	VDL4	VDL4
	14	-Mode A/C -Squitter Tx -VDL4 Tx/Rx	TCAS Squitter	TCAS Squitter VDL4	TCAS Squitter VDL4	TCAS Squitter	Squitter	VDL4	Squitter VDL4	Squitter VDL4	VDL4

2.4 Multi-Link Ground Configurations

Table L-4 represents the range of potential ground configurations for single and multiple link systems to support ADS-B Air-Ground applications, TIS-B, and Ground Gateway Multi-Link ADS-B. Compatible avionics configurations are tabulated with reference to Table L-1.

Table L-4: Single and Multi-Link ADS-B Air-Ground, TIS-B, and Ground Gateway Configurations

Gnd Config	Squitter		UAT		VDL4		Compatible Avionics Config	Supported Applications		
	T	R	T	R	T	R		ADS-B A-G	TIS-B	Ground Gateway
A		Ö					ACB, GAB, 1, 2, 3, 5, 7, 8, 9, 10, 12, 14	Ö		
B				Ö			1, 3, 4, 5, 6, 7	Ö		
C						Ö	8, 10, 11, 12, 13, 14	Ö		
D	Ö	Ö					ACB, GAB, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14	Ö	Ö	
E			Ö	Ö			1, 2, 3, 4, 5, 6, 7	Ö	Ö	
F					Ö	Ö	8, 9, 10, 11, 12, 13, 14	Ö	Ö	
G		Ö		Ö			ACB, GAB, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14	Ö		
H		Ö				Ö	ACB, GAB, 1, 2, 3, 5, 7, 8, 9, 10, 11, 12, 13 14	Ö		
I	Ö	Ö	Ö	Ö			ACB, GAB, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 13, 14	Ö	Ö	Ö
J	Ö	Ö			Ö	Ö	ACB, GAB, 1, 2, 3, 5, 7, 8, 9, 10, 11, 12, 13 14	Ö	Ö	Ö
K		Ö	Ö	Ö			ACB, GAB, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14	Ö	Ö	
L	Ö	Ö		Ö			ACB, GAB, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12 14	Ö	Ö	
M		Ö			Ö	Ö	ACB, GAB, 1, 2, 3, 5, 7, 8, 9, 10, 11, 12, 13 14	Ö	Ö	
N	Ö	Ö				Ö	ACB, GAB, 1, 2, 3, 5, 7, 8, 9, 10, 11, 12 13, 14	Ö	Ö	
O		Ö		Ö		Ö	ACB, GAB, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 12, 13, 14	Ö	Ö	
P	Ö	Ö	Ö	Ö	Ö	Ö	ACB, GAB, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 12, 13, 14	Ö	Ö	Ö

ACB = Air Carrier baseline configuration from Tables L-3 and L-4
GAB = General Aviation baseline configuration from Tables L-3 and L-4

Table L-4 is based on the following conditions:

- TIS-B may be broadcast from the ground using one or more than one of the available link technologies

- Support for Air-Ground ADS-B applications indicates that the aircraft is able to transmit ADS-B that can be received by the ground station.

- Where Ground Gateway multi-link ADS-B is in use, each ground site must be able to receive, cross-link, and transmit on any of the links in use.

3.0 Shared Use of Airborne System Components at L-Band

Multi-link architectures suggest shared use of key system components, such as antennas and power amplifiers, to leverage high-cost components for multiple applications. Shared use at L-Band may be possible for certain transponder system components such as antenna and power amplifier, while L-Band/VHF may allow use of the VHF communication antenna system.

Shared use at L-Band is indicated by the relatively low utilization rates for Mode S transponder/Extended Squitter ADS-B, DME, and UAT ADS-B systems as shown in Table L-5. Issues with shared use include:

- Required filter Q and cost of high peak power (500w) cross-over filter for shared use of transponder antenna with separate UAT transceiver

- Potential suitability of transponder pulse waveform power amplifier for lower power CPFSK UAT waveform in dual mode transponder and UAT transceiver.

Table L-5: Mode S Transponder/Extended Squitter ADS-B, DME and UAT Utilization at L-Band

System	Utilization by Function	Total Utilization (s)
Mode S Xpdr/ Extended Squitter ADS-B (1090 MHz)	- 400 Mode A/C replies/sec @ 20us/reply = 0.008 - 10 Mode-S replies/sec @ 60 us/reply = 0.0006 - 6 Squitters/sec @ 120 us/message = 0.0007	0.009
DME (1025-1150 MHz)	- 150 interrogations/sec @ 45 us/interrogation = 0.007	0.007
UAT (981 MHz)	- 1 message/sec @ 372 us/message = 0.0004	0.0004
	Total L-Band Utilization	**0.02**

Figure L-3 represents a possible configuration for a Extended Squitter/UAT or DME/UAT system sharing a common antenna and utilizing a band-pass filter and inhibit circuit.

In terms of utilizing other transponder components, Figure L-4 represents a baseline Mode-S transponder system, while Figure L-5 shows that system modified for Extended Squitter ADS-B. Figure L-6 illustrates a potential 1090/UAT configuration sharing a common power amplifier and antenna.

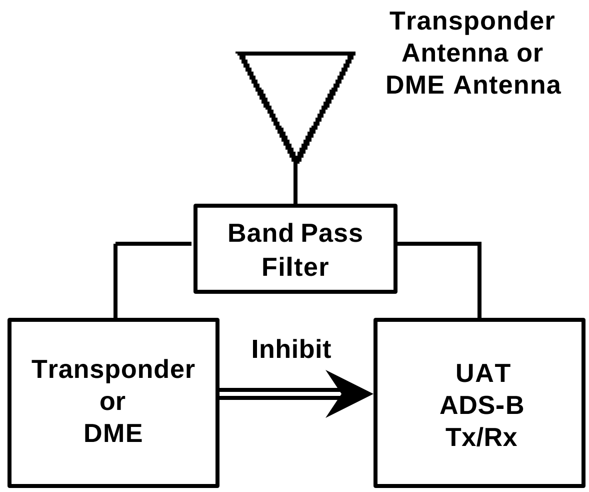


Figure L-3: Shared Use of Transponder/Extended Squitter ADS-B Antenna or DME Antenna for UAT ADS-B

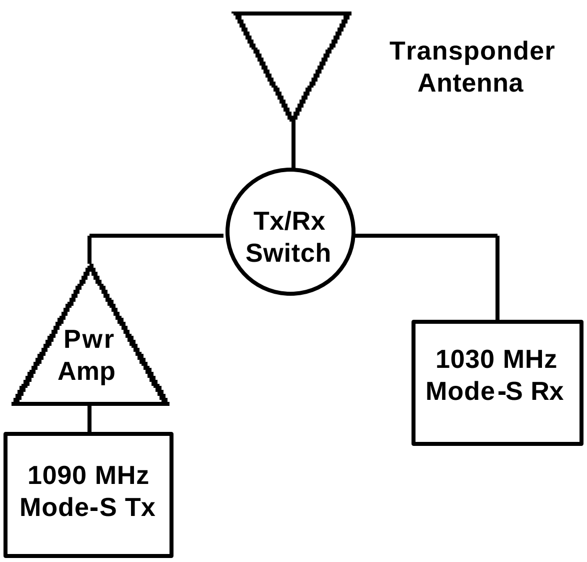


Figure L-4: Baseline Mode -S Transponder Configuration

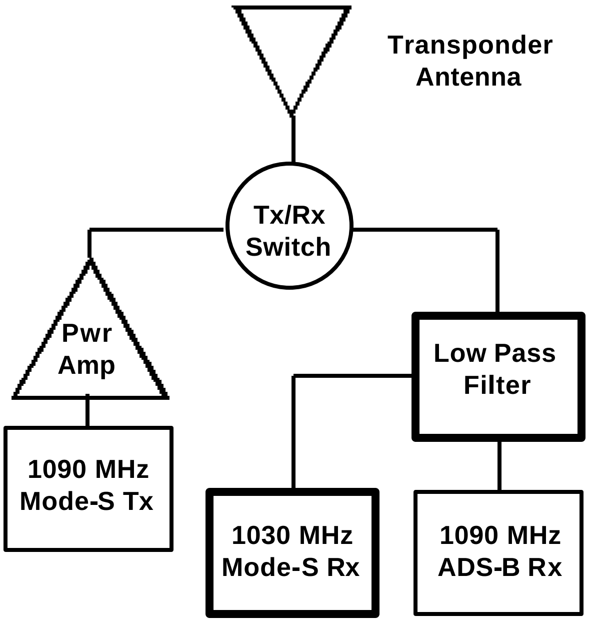
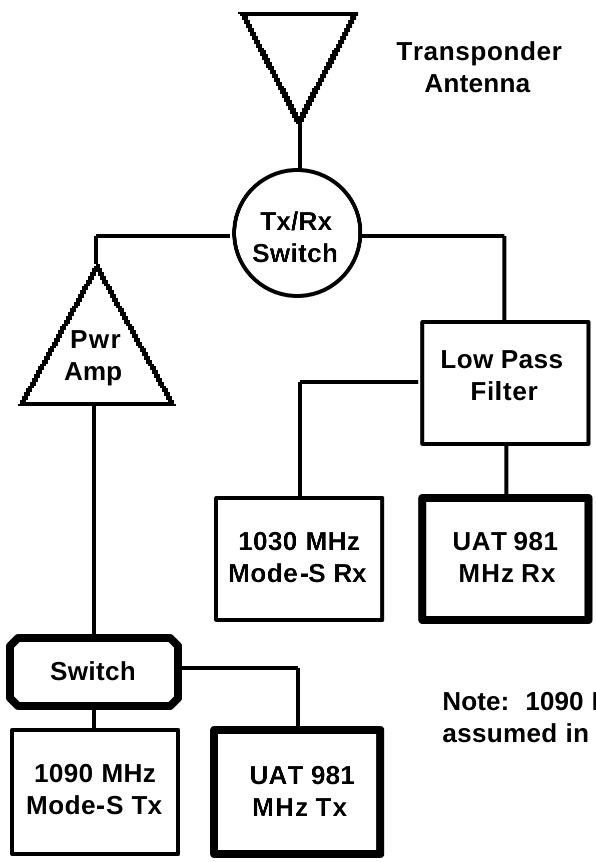


Figure L-5: Mode-S Transponder-Based Extended Squitter ADS-B Configuration



Note: 1090 MHz ADS-B Rx assumed in modified TCAS

Figure L-6: Mode-S Transponder-Based 1090 MHz/UAT Multi-Link ADS-B Configuration

4.0 Potential VDL Mode 4 System Baseline Single -Link System Architectures

Figure L-7 is a baseline, high-level schematic of a Extended Squitter/VDL Mode 4 multi-link system. Figures L-8 and L-9 are based on those presented by Dr. Armin Schlereth during his October 16, 2000 briefing to the TLAT titled, *System Description for VDL Mode 4 Proposed for Link Assessment of the Safe Flight 21 Applications*. The component abbreviations refer to the essential power distribution buses (ESS BUS), Global Navigation Satellite System (GNSS), Inertial Reference System (IRS), Communications Management Unit (CMU), Flight Management System (FMS), and Electronic Instrument System/Electronic Flight Instrument System (EIS/EFIS).

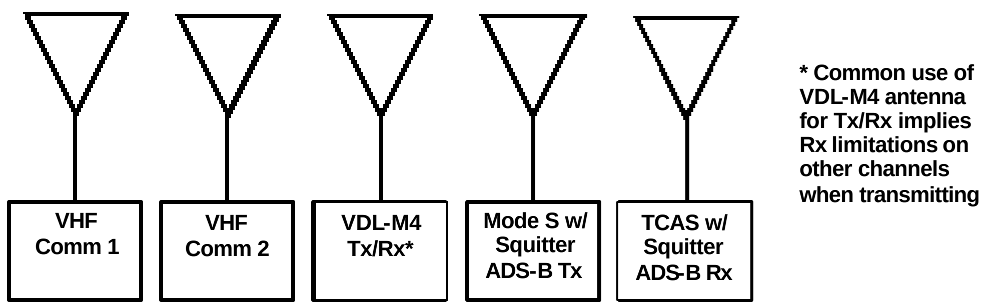


Figure L-7: VDL-M4 with Mode-S Squitter

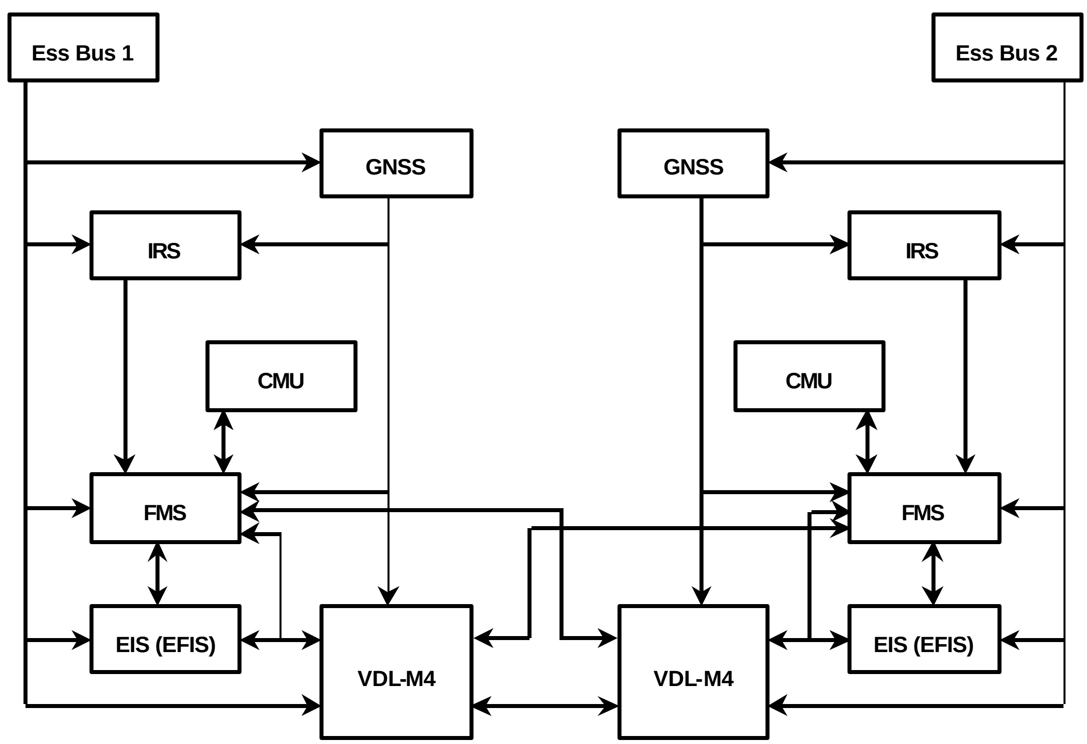


Figure L-8: Example of Commercial Aircraft Architecture for Stand-Alone VDL Mode 4 Transceiver

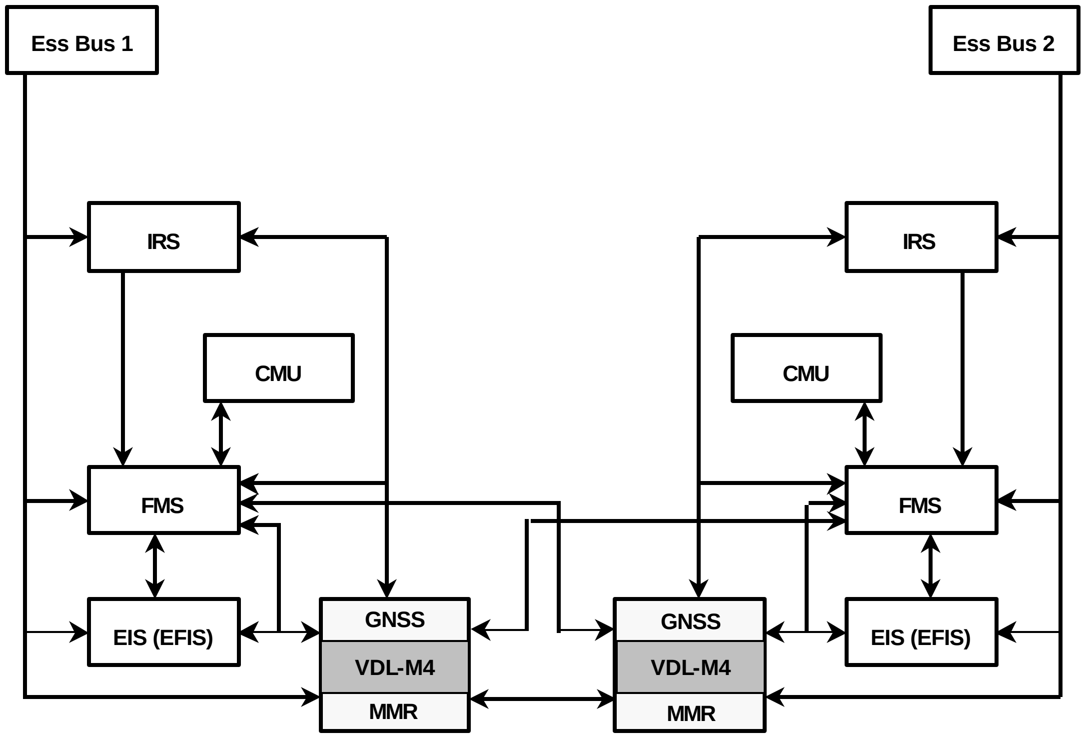


Figure L-9: Example of Commercial Aircraft Architecture for Stand-Alone VDL Mode 4 Transceiver

Appendix M
Further Analyses

Appendix M.1

Technical Findings Regarding the ADSI VDL-4 Channel Management Plan

JHU/APL

March 2001

1.0 Background

APL was tasked to evaluate an alternative approach to VDL Mode 4 channel management for the LA Basin, referred to as the "honeycomb" scheme. The concept was documented in several ADSI sources. APL authored a document that contained a description of the approach and plans to conduct an analysis of the approach, Ref. [1]. The briefings presented at the February and March TLAT meetings are the source of the technical results provided in this document.

2.0 Analysis Plan Summary

A summary of the analysis plan is presented in this section with further detail found in Ref. [1].

2.1 Baseline Traffic Scenario

The baseline traffic scenario consists of 2694 aircraft postulated for the LA Basin in the year 2020. The goals of the baseline traffic scenario were to:

- Determine if capacity is sufficient for GND channel users (ideal performance)
- Determine if capacity is sufficient for uniformly tiled LSC and GSC 2 (ideal performance)
- Analyze GND and LSC/GSC2 with receiver performance model
- Analyze capacity and performance in retiled case

2.2 Sensitivity Analysis

A sensitivity analysis was included in order to determine how the approach would work with other instantiations of the LA Basin scenario.

2.3 Qualitative Issues

This portion of the analysis task was focused on non-quantitative engineering considerations. These resulted from the ADSI documentation and from the quantitative assessment. This part of the analysis plan also was used to recommend areas for further analysis.

3.0 Results

Results from the analysis were presented at the February TLAT meeting held at APL. At that time the following items were completed:

- GND and LSC/GSC2 capacity was analyzed for the baseline scenario and 3 other scenarios (sensitivity analysis)
- Receiver performance analysis has been conducted for simple LSC/GSC2 interference case between two tiles
- Some qualitative issues with the approach were determined

3.1 GND and LSC/GSC2 Capacity

The capacity required for the transmission of ADS-B message was found by considering the membership of each tile, i.e., the number of aircraft in the tile and considering the per-aircraft transmission rates which were a function of the location of the aircraft. It was found that the capacity of the inner tile was insufficient to support the number of users for both the LSC and GSC2 channels in the baseline scenario and in the other three instantiations. It was found that the cluster of 7 inner tiles possessed adequate capacity to support the message traffic if some retiling approach could be developed.

Figure 1 shows the tile membership. The xy-plane units are tile identifiers. The tile grid to cover the LA basin was modeled as 20 by 18 tiles. The z-axis units are the numbers of aircraft in each tile. The center tile contains 150 aircraft and the 7-tile cluster in the center contains 370 aircraft.

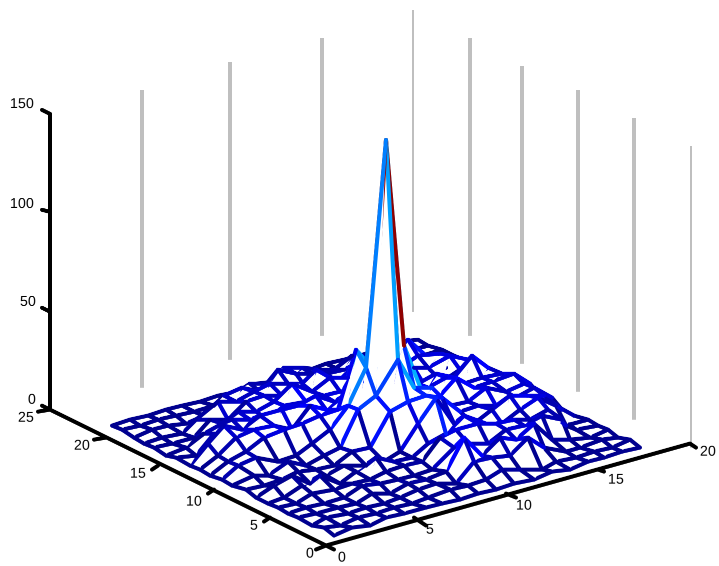


Figure 1. Tile Members

The required message transmission capacity for the GSC 2 channel is shown in Figure 2. The z-axis units are ADS-B messages per minute (msg/min). The center tile requires a transmission capacity of 1336 msg/min and the 7-tile cluster requires 3252 msg/min. A simple analysis of the channel management scheme shows that the capacity per tile is 512 msg/min and therefore, 3584 for any 7-tile cluster. Therefore the center tile capacity of the ADSI approach is not adequate to support the required GSC 2 traffic. The 7-tile cluster can support the required transmissions however.

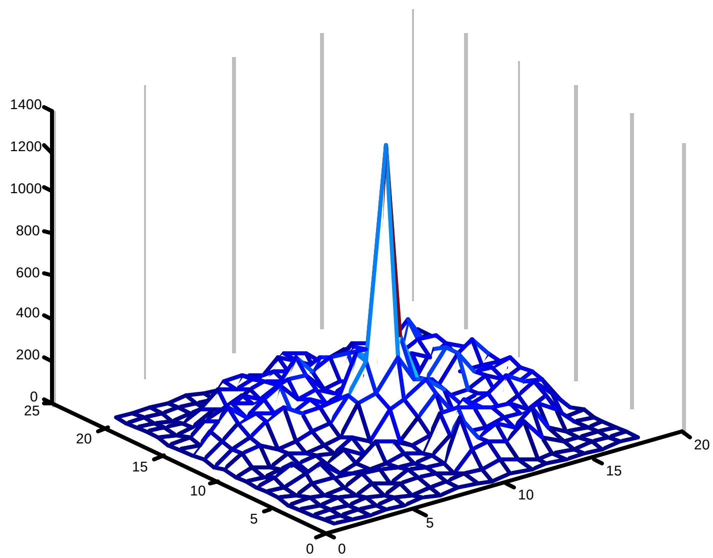


Figure 2. Required Message Capacity (GSC 2)

The LSC case is similar to GSC 2 but the required rates are somewhat lower. The required message capacity is shown in Figure 3. The capacity offered by the ADSI approach is the same for LSC and GSC2 so 512 msg/min is the highest transmission rate which can be supported by the scheme. The center tile requires 1152 msg/min and the 7-tile center cluster requires 2832 msg/min. The approach is inadequate to support the center tile demand but retiling of the center cluster may provide enough capacity in this ideal case.

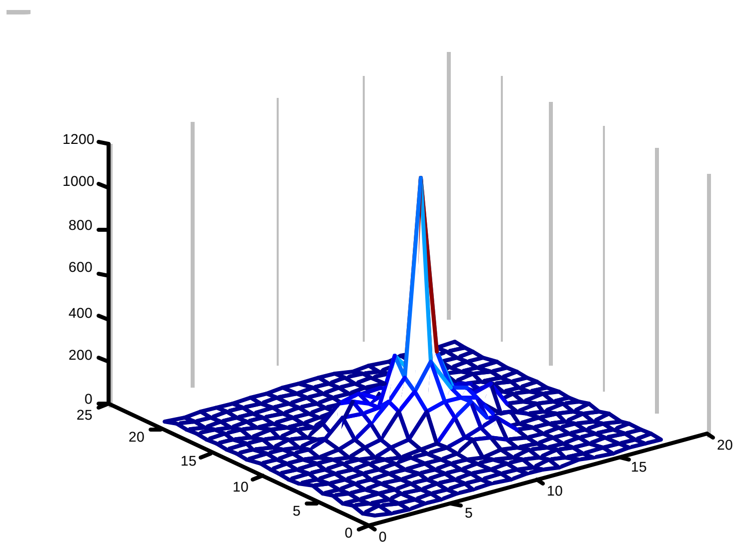


Figure 3. Required Message Capacity (LSC)

The other three scenarios run for the approach yield similar results. The other three scenarios yield the following center tile and center cluster required capacities (in msg/min):

- Scenario 2: 1184/3180 (GSC 2); 1008/2696 (LSC)
- Scenario 3: 1216/3344 (GSC 2); 1072/2880 (LSC)
- Scenario 4: 1396/3352 (GSC 2); 1104/2728 (LSC)

Therefore, retiling must be attempted if the approach is to succeed. Retiling may be restricted by low-altitude, coverage limitations.

The GND channel capacity was analyzed in a similar manner. There are 225 aircraft in the scenario that are located at several airports in the LA basin region. These aircraft are shown in Figure 4 in clusters representing each airport (units in nmi from center of scenario). The capacity of the GND channel is 120 users stationary and 69 users moving. These can easily be derived with the description of the GND channel contained in Ref. [1]. Figure 5 shows the capacity at each of the airports that are indicated by the clusters in Figure 4. This was generated for the first of the LA scenarios. The other scenarios generate similar plots. The number of moving aircraft did not exceed 45 and the number of stationary aircraft did not exceed 40.

This analysis only considers transmission capacity and indicates that the ADSI technique allows enough capacity to support those four LA scenarios. The primary question remaining is how signals from each airport would interact with each other. It is possible that there would exist too much interference from closely-spaced airports that slots could not be simultaneously used. This would depend on a variety of propagation issues including terrain effects. There was inadequate time to determine these effects due to the depth of the analysis required.

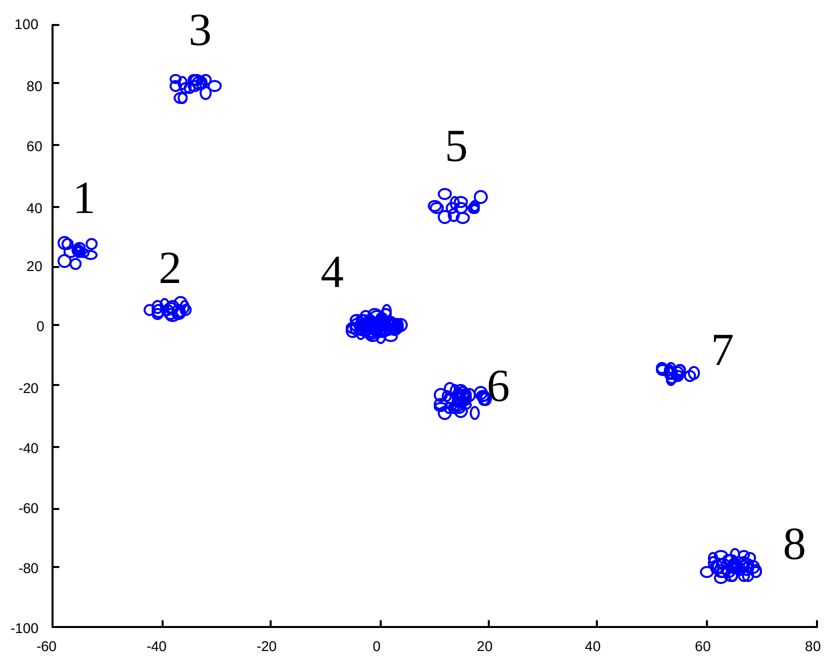


Figure 4. Ground Aircraft at LA Airports

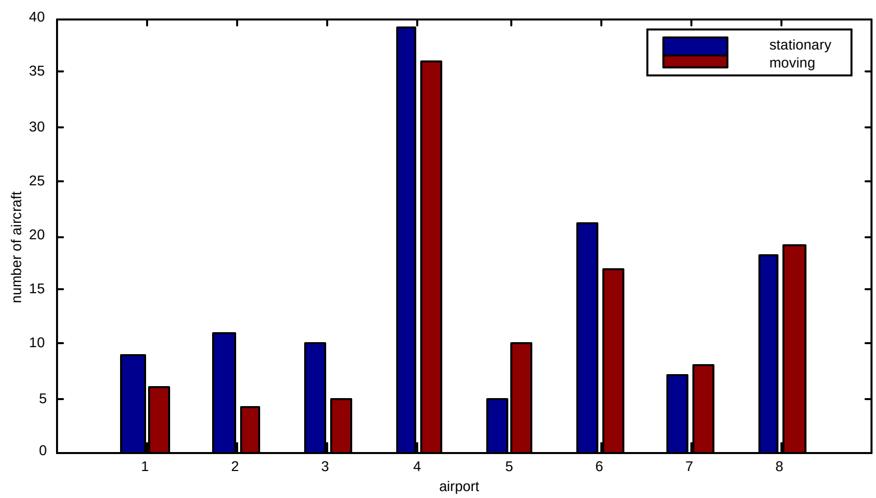


Figure 5. Capacity for LA Scenario 1

3.2 Simple Receiver Performance Cases

Several simple two-transmitter cases were examined to determine the MER as a function of receiver placement. The two cases represent transmitters that could be sharing a slot at close and far distances. These are depicted in Figure 6. The transmitters were placed at the center of the tiles indicated. The receiver was placed on a line connecting the two tiles.

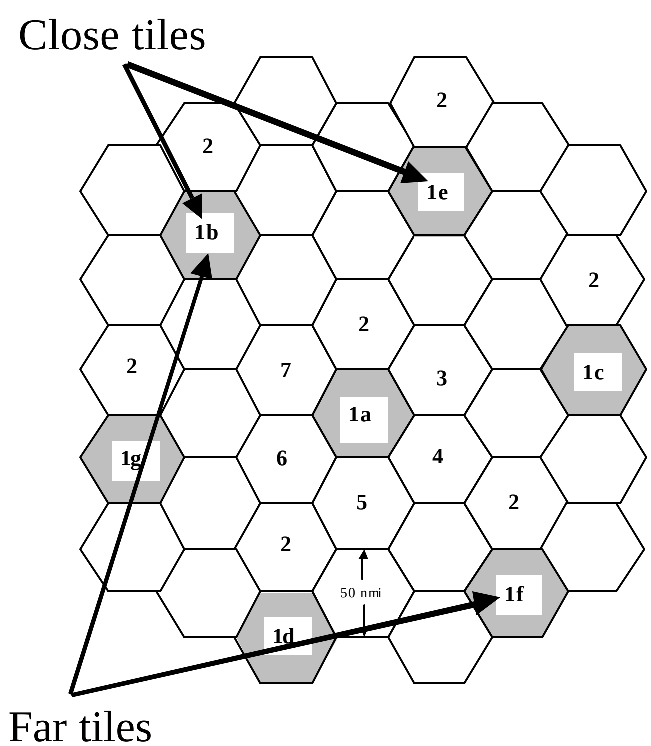


Figure 6. Two-Transmitter Cases

The MER performance for the two cases is shown in Figures 7 and 8. As indicated from these plots, significant regions exist between tiles where a user would not be able to reliably receive either transmission if those users are sharing a slot. This simple analysis indicates the importance of the slot assignment algorithm that is employed. The slot assignment algorithm could enable slots that are shared between users in same-numbered tiles to cycle to another slot in the frame on a subsequent transmission. This would be beneficial for the effective update times.

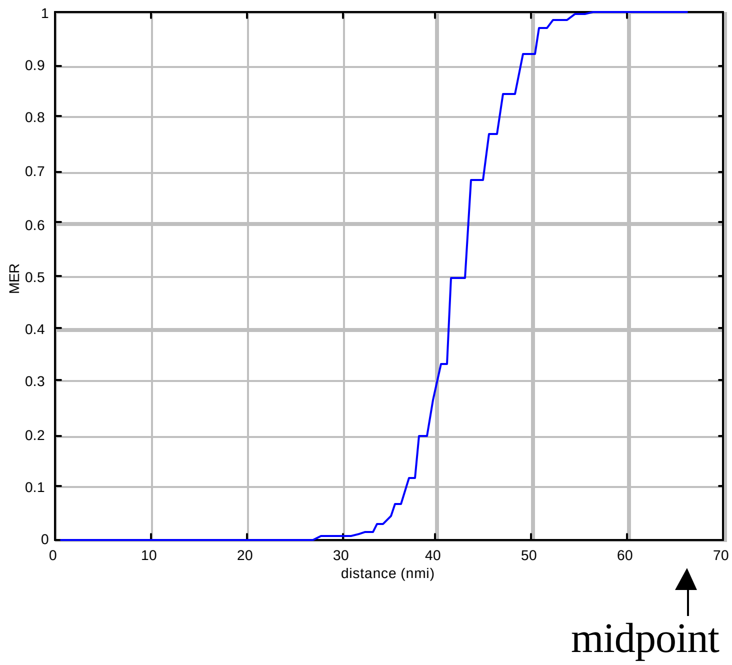


Figure 7. MER Performance (Close)

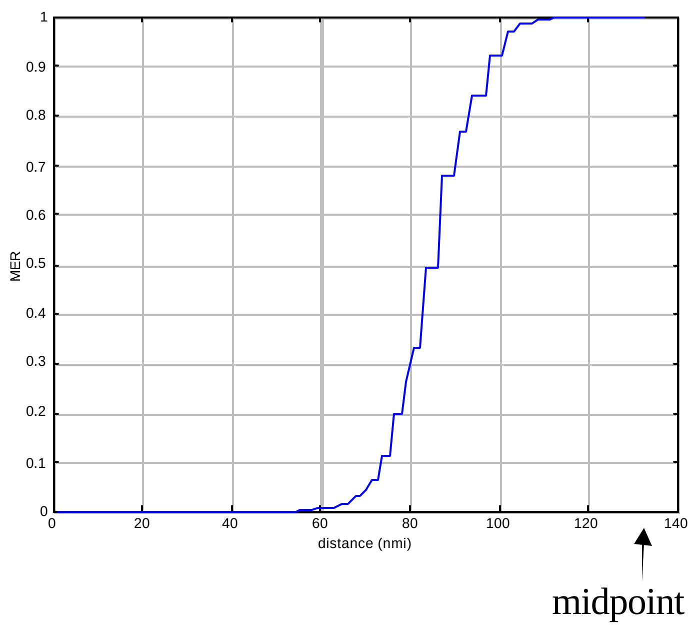


Figure 8. MER Performance (Far)

3.3 Slot Assignment Analysis

Following the February TLAT meeting, APL and ADSI determined a set of issues to investigate. The retiling/slot assignment algorithm was the primary area that required further definition. Retiling is essentially embedded in the slot assignments. The continued analysis would focus on one of the tiled channels and would be directed to determine effective update intervals.   The following steps were executed to support completion of the analysis by the March TLAT meeting:

• APL will provide a set of aircraft locations representing consecutive snapshots of the LA Basin (no more than 10) to ADSI by 2/21/01

• ADSI, using their software, will use this set of aircraft locations to determine a set of slot assignments and provide these to APL by 2/26/01

• APL will integrate the appropriate performance models into the simulation as well as analyze the data produced from the simulation and present the results

Some other tasks were proposed but were not included in the follow-on studies. These included the following:

• The TCP messages should be included since they represent a non-trivial load thus their slot assignments would be needed

• Both tiled channels (LSC and GSC2) should be included in the analysis in order to determine the effective message update rates to avoid assumptions extending single-channel results

• The air-to-ground and ground-to-air transmissions should be included in the slot assignments since those messages are important to the operation of the approach. This would require the definition of ground nodes and their respective slot assignments.

The analysis was conducted between the February and March TLAT meetings. A schedule slip of a little over a week was incurred due to the slot assignments being provided to APL from ADSI late. The technical results in this section indicate those completed tasks presented at the March TLAT meeting. At the time of this writing, the analysis up to the Monte Carlo runs has been completed.

MER results were generated from a simulator that utilized the APL receiver performance model. The one aspect of the transmission path not included was the transmit and receive antenna gain function. Fixed 3 dB gains were used for the transmit and receive antennas.   The analysis spanned a 9 minutes segment of time that employed 9 sets of slots assignments each utilized for one minute.

Three aircraft were used in the analysis as shown in Figure 9 with their relative positions in the LA scenario.

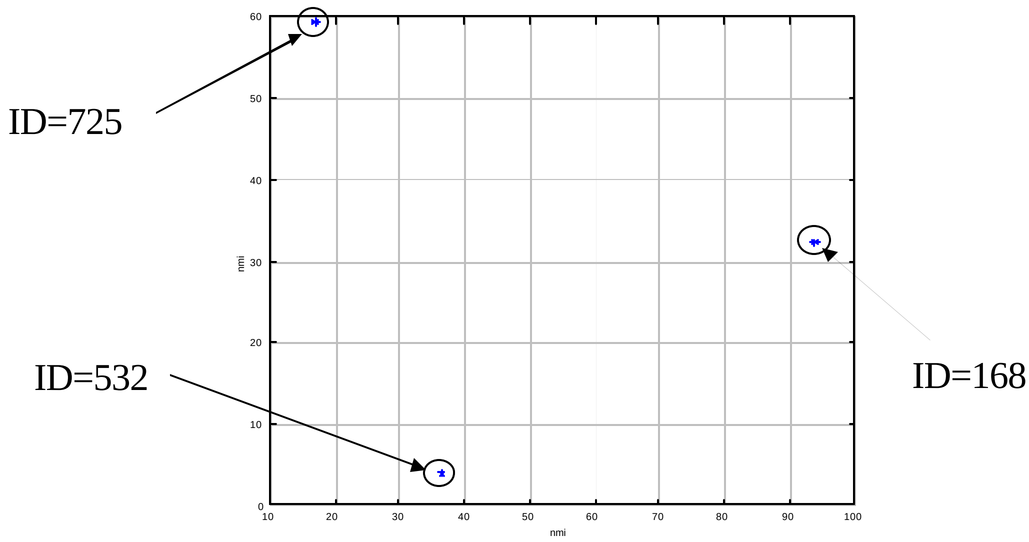


Figure 9. Subject Aircraft for MER Analysis

The MER histogram over the 9 minute time span is shown for the three aircraft in Figures 10, 11 and 12. These show that the number of messages received with low MER is decreasing as the subject aircraft is further from the center of the scenario. Since the density of aircraft is concentrated in the center, it is conjectured that the performance is worsening with decreasing aircraft density.

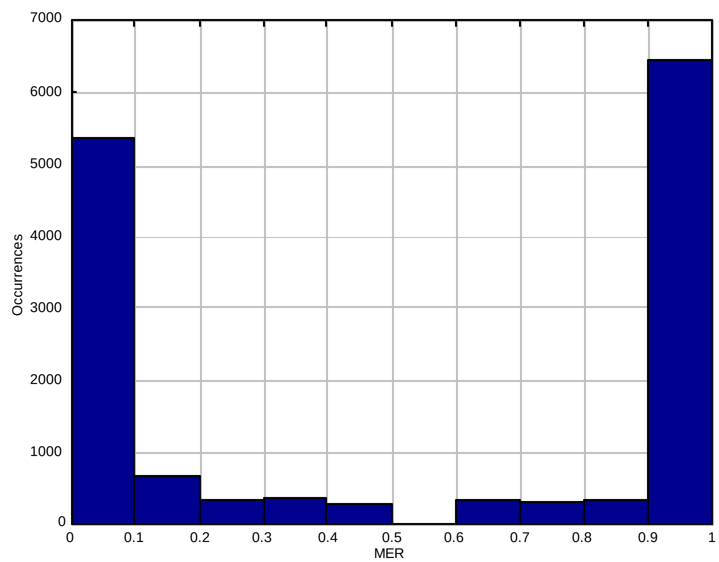


Figure 10. MER Histogram for Aircraft 532

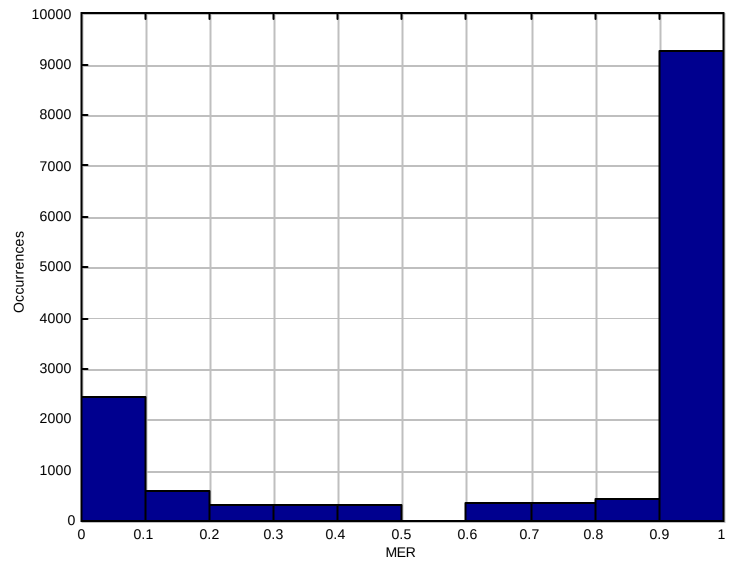


Figure 11. MER Histogram for Aircraft 725

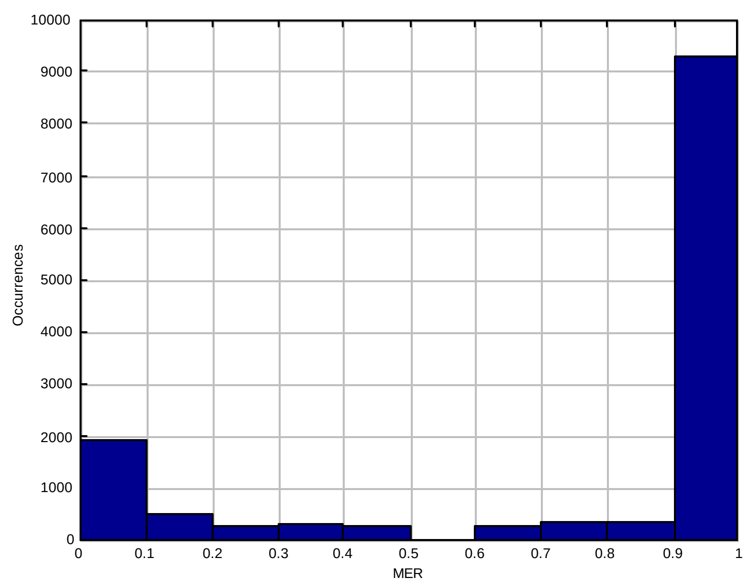
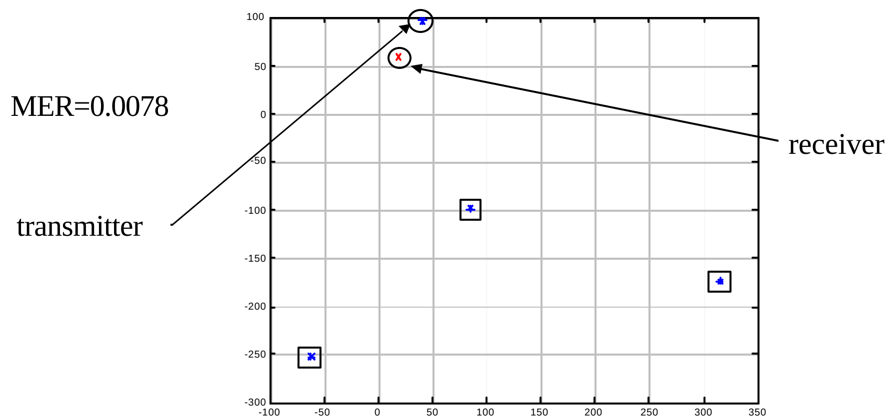


Figure 12. MER Histogram for Aircraft 168

MER performance as a function of distance is characterized by increasing message errors as the distance increases between transmitter and receiver. The Monte Carlo analysis is necessary to determine the effective update rates based on MER values for individual aircraft. However, this effective update rate only will pertain to GSC2. The tiling approach is also used on LSC and thus the total effective update rate is going to be based on receptions on both channels. Some bounding techniques can be used on effective update but a combined simulation is necessary to get accurate statistics.

Several cases of low and high MERs were analyzed to determine what the fundamental causes may be for this technique. Figure 13 shows an example of a low MER case and Figure 14 of a high MER case. As can be seen, both cases show a large distance between users sharing a slot but the proximity of the receiver relative to the interferers is somewhat different. This is a fundamental issue that was briefly discussed in the simple two-transmitter cases - the distance between transmitters sharing a slot is not the only consideration for effective transmissions. The location of the receiver in the scenario is also important. Significant regions between transmitters sharing a slot will not allow for successful message transmission due to the inadequacy of the SNR and SIR values.



Other users sharing same slot are shown (in boxes)

Figure 13. Low MER Case

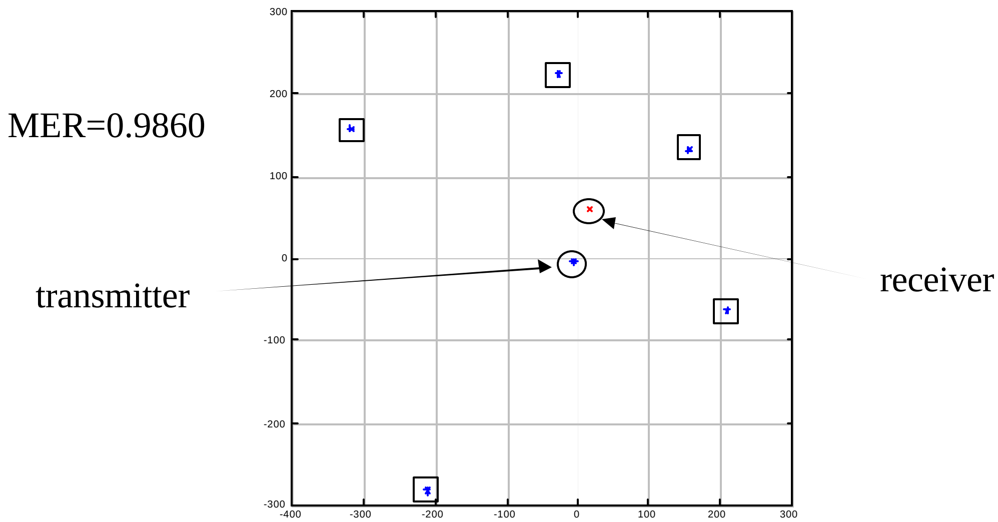


Figure 14. High MER Case

4.0 Qualitative Assessment

Many qualitative issues have come from the analysis and from engineering judgement regarding the concept. These are as follows:

• Ground Network: The analysis has assumed an “omniscient” ground network which can make choices for slot assignments in a timely fashion. The GND channel assignments to stationary/mobile slots rely on ground network knowledge of aircraft motion. The LSC/GSC2 assignments depend on ground network knowledge of aircraft locations in tiles and entering and exiting the tiled region. The feasibility of this ground network and the implications for failure (of the processing systems and slot assignment transmissions to aircraft) should be studied further.

• TCP Support: The ability of the technique to support TCP transmissions was not proposed in the documentation to the degree that an analysis could be done.

• Slot Assignment Algorithm: The slot assignments from ADSI were generated with a tool that was, in ADSI terms, a "first strawman". It is certainly possible that further development of these algorithms would allow for improved performance of the technique.

Finally, other excursions (changing LSC/GSC2 reporting rates, region changes, etc.) that were discussed in ADSI documentation have not been able to be investigated in depth and should be studied further.

5.0 Summary

This document summarizes the findings of a study of ADSI channel management approach for VDL Mode 4 in the LA Basin. These results were based on an analysis plan, Ref. [1], and follow-up analyses determined by APL and ADSI. Various quantitative performance measures have been shown and findings cited. Finally, qualitative issues have been captured for further investigation.

6.0 Reference

[1] "ADSI VDL-4 Channel Management Plan: Assumed Operational Characteristics and Analysis Plan," JHU/APL, December 2000 (revised January 2001).

APPENDIX M.2

VDL MODE 4 SLOT SELECTION
SENSITIVITY EXAMINATION

M.2.1 Introduction

Optimal coverage in a VDL Mode 4 net occurs when each net member transmits on a clear slot. In this case range is typically limited by radio horizon rather than by signal to interference conditions associated with simultaneous transmissions on the same slot by two users. Estimated bounds on the availability of clear slots for use in a three channel VDL Mode 4 configuration are made under the following assumptions:

1) Selection of clear slots on each channel is limited only by the distribution of clear slots on that channel and the knowledge each user has of that distribution.
2) Since multiple net members are attempting to achieve a somewhat uniform distribution of used slots, it is assumed that the resulting distribution of clear slots over the one minute frame of 4500 slots is approximately random.

With these assumptions, the probability of selecting a clear slot is compared with the probability of selecting two adjacent clear slots (for the 2-slot message employed to broadcast intent information). These probabilities are compared as a function of the number of users in the net, M, and for the following limiting conditions:

1) Each net member has full knowledge of the availability of clear slots and the selection is limited by only the availability of clear slots within a permitted slot dither interval, b, slots (upper bound).
2) Some fraction, a, of the m net members selecting a new slot in each frame are unaware of clear slot availability and select a new slot at random (lower bound).

Sensitivity of these clear new slot selection probabilities to the permitted dither interval are examined for b = 37 slots and b = 255 slots.

M.2.2 Clear 1-Slot Selection

Notation used is defined in Figure 1. Based on the slot use example in the VDL Mode 4 System Description, determination of, s, the number of slots/user/frame/channel is also described in this figure. The results, shown in Figure 2 are so = 4 slots/user/minute/GSC. With M users on the channel and "so" slots/user, there are k = 4500 – so x M available clear slots in the frame. The probability of a clear slot is then Pi = k / 4500. If each slot is reselected on an average interval of ts seconds, then m = so x M / ts new slot selections are made in each frame.

Probability of a clear slot selection from b available, P1, and probability of success when contending for a clear slot, Pc1, are given in the lower part of Figure 2 in terms of the above parameters. These probabilities of clear 1-slot selection (limited only by the distribution), P1, and clear 1-slot contention, Pc1, are graphed as a function of M in Figure 3 for so = 4, ts = 6, a = 0.25, and b = 37. For these values, M = 1050 at P1 = 0.9, and M = 800 at Pc1 = 0.9. Similar plots for the regional signaling channel, RSC, with so = 10 yield M = 450 and M = 325 for P1 = 0.9 and Pc1 = 0.9 respectively.

M.2.3 Clear 2-Slot Selection

Expressions estimating the availability of at least two contiguous clear slots, P2, or approximating success in contention for two adjacent clear slots, Pc2, are given in Figure 4. This figure also graphs these 2-slot probabilities for the same GSC assumptions as Figure 3. In this case the 90% probability standard for capacity limits are M = 800 for P2 and M = 325 for Pc2. Use of the 2-slot message with a slot dither interval of 37 slots reduces capacity to about 80% of that estimated for 1-slot use in the P1 limiting case and by about 40% in the contention limiting example.

M.2.4 Use of a Larger Slot Selection Interval

The probability of two adjacent clear slots occurring in an interval increases as the slot selection interval increases (for a fixed slot utilization level). Although VDL Mode 4 plans to use a slot dither interval of b = 255, computation of curves such as Figures 3 and 4 for this value of b were limited by the large factorial values associated with the P2 estimate. Nevertheless, results for b = 150 illustrate general behavior of increased slot dither intervals. For b = 150, M = 1100 (full slot utilization), indicating no capacity reduction with full knowledge of the distribution. For this approach to 2-slot contention estimation, no change in the associated Pc2 value. In summary, with a 90 % probability of clear slot success as a standard of comparison between one slot and two slot selection with a larger value of b, a reduction of 40 – 100 % for available two slot selections is estimated. The lower value comes from the assumption of 25% slot contention. Simulations indicate VDL Mode 4 performance starts to drop at a contention level of about 15%.

M = average number users/channel for 4500 slots/min/channel
s = average number slots/user/minute/channel
ts = average interval (min) between user selection of new slot
m = number new slot selections/min/channel
k = number unused slots/min/channel available for selection
C = m/k, ratio of new slot selections to unused slots available
Pi = probability slot is unused
P1 = probability selecting unused 1-slot message out of b available
P2 = probability selecting unused 2-slot message out of b available
Pc1 = probability contending for unused 1-slot message
Pc2 = probability contending for unused 2-slot message
e = slot assignment utilization effeciency
fe = fraction users in low density airspace
fh = fraction users in high density airspace
Tu = average broadcast interval in sec
a = fraction of slot selections made w/o accurate current slot use table

Slots/user/min/channel: GSC-1, sg1; GSC-2, sg2; and regional-1, sr1

GSC-1 low density $se1 := \frac{6}{2} + \frac{5 + 1 \cdot 2}{2}$

GSC-2 low density $se2 := \frac{5 + 1 \cdot 2}{2} + \frac{6}{2}$

GSC-1 high density $sh1 := \frac{1 \cdot 2}{2} + \frac{1}{2}$

GSC-2 high density $sh2 := \frac{1}{2} + \frac{1 \cdot 2}{2}$

Traffic distribution: $fe := 0.5$ $fh := 0.5$

Regional-1 $sr1 := \frac{10}{2} + \frac{10}{2}$

Figure 1

Traffic distribution: $fe := 0.5$ $fh := 0.5$

Regional-1

$sr1 := \frac{10}{2} + \frac{10}{2}$

Average channel rates:

$sg1 := fe \cdot se1 + fh \cdot sh1$ $sg2 := fe \cdot se2 + fh \cdot sh2$ $sg1 + sg2 = 8$ $sg1 + sg2 + sr1 = 18$

$sg1 = 4$ $sg2 = 4$ $sr1 = 10$ Low & high density state vector brcst intervals:

$se := (se1 - .5) + (se2 - .5)$ $sh := (sh1 - .5) + (sh2 - .5) + sr1$ $se = 12$ $sh = 12$

Run conditions: $so := 4$ $ts := 6$ $e := 0.99$ $a := 0.25$ $b := \mathrm{floor}\left(0.1 \cdot \frac{4500}{se}\right)$ $b = 37$

$Mx := \frac{4500 \cdot e}{so}$ $M := 10, 20 .. Mx$ $Mx = 1114$ $Tu(si) := \frac{60}{si}$ $Tu(se) = 5$ $Tu(sh) = 5$

$k(si, M) := 4500 - si \cdot M$ $m(si, M) := si \cdot \frac{M}{ts}$ $C(si, M) := \frac{m(si, M)}{k(si, M)}$ $Pi(M, si) := \frac{k(si, M)}{4500}$

1-Slot selection from b available:

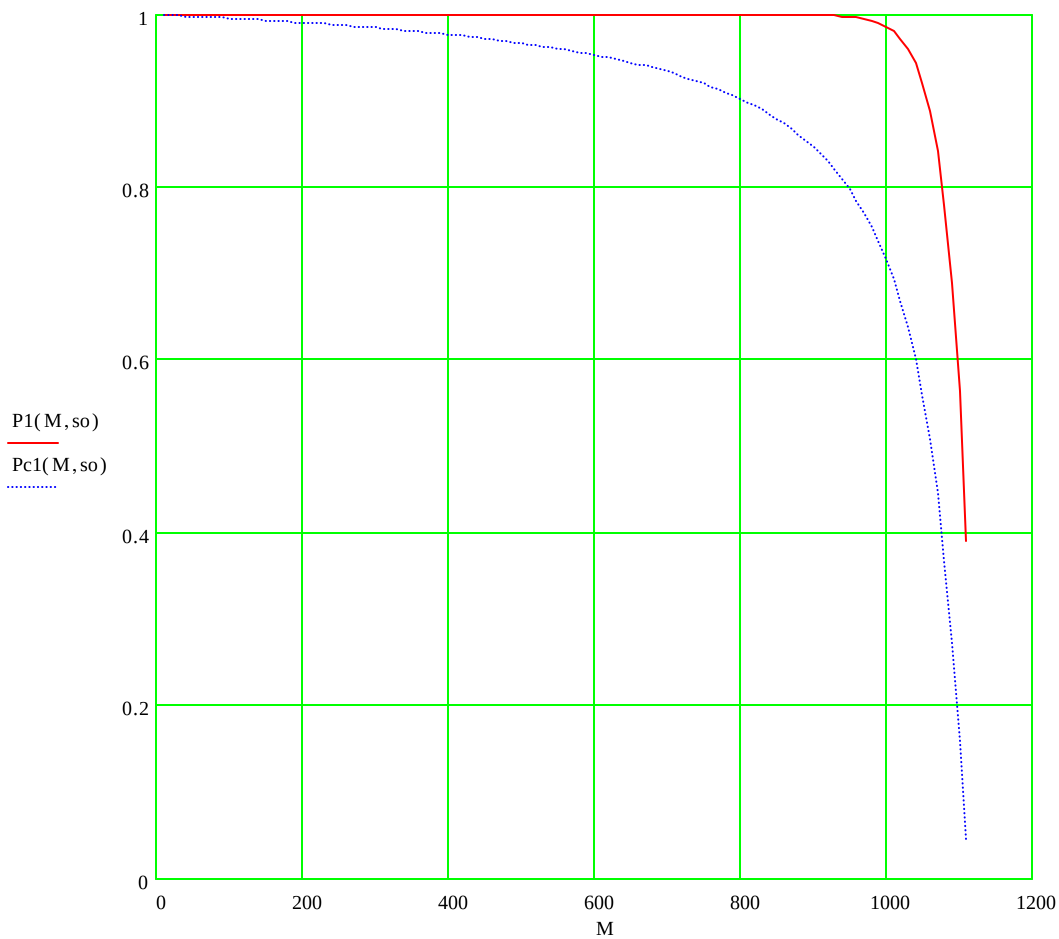
$$P1(M, si) := 1 - (1 - Pi(M, si))^{b}$$

1-Slot contention for a x m new selections from k slots where a = fraction of selections not seen:

$$Pc1(M, si) := \left(1 - \frac{1}{k(si, M)}\right)^{a \cdot m(si, M) - 1}$$

Figure 2

$so = 4 \quad ts = 6 \quad b = 37 \quad e = 0.99 \quad a = 0.25$



Probabilities of clear 1-slot selection, P1, and clear 1-slot contention, Pc1, vs number users/channel, M, for so slots/min/user/channel and ts minutes between slot selection (for random distribution). Assumes fraction, a, of selections are in contention for Pc1.

Figure 3

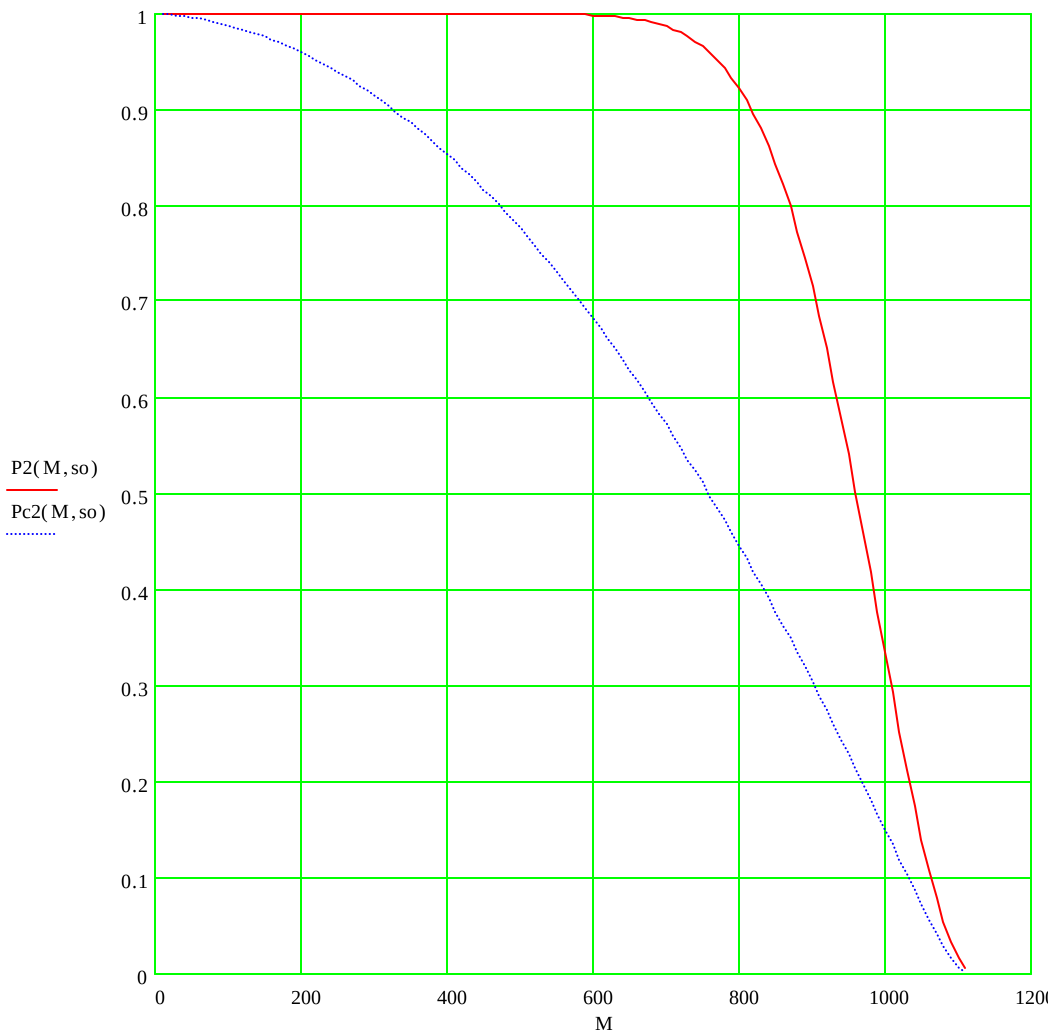
Selection of at least two adjacent clear slots out of b available:

$$B := b \qquad FF(B,i) := \mathrm{if}\left(\frac{B+1}{2} \geq i, \frac{(B-i+1)!}{(B+1-2\cdot i)!\cdot i!}, 0\right)$$

$$P2(M,si) := \sum_{i=2}^{B}\left(\frac{B!}{(B-i)!\cdot i!} - FF(B,i)\right)\cdot Pi(M,si)^{i}\cdot(1-Pi(M,si))^{B-i}$$

Slot contention with adjacent slot also clear: $Pc2(M,si) := Pc1(M,si)\cdot\left[1-(1-Pi(M,si))^{2}\right]$

$so = 4 \qquad ts = 6 \qquad b = 37 \qquad e = 0.99 \qquad a = 0.25$



Probabilities of clear 2-slot selection, P2, and clear 2-slot contention, Pc2, vs number users/channel, M, for so slots/min/user/channel and ts minutes between slot selection (for random distribution). Assumes fraction, a, of selections are in contention for Pc2.

Figure 4

Appendix M.3 Transition between VDL Mode 4 regions

The TLAT VDL Mode 4 System Description envisages the use of four VHF channels (two Global and two Regional Signaling Channels) in the Core Europe 2015 and Los Angeles Basin 2020 scenarios. In either scenario the internal airspace is divided into two regions. All aircraft receive on all four channels and transmit on the two Global Signaling Channels and one of the two Regional Signaling Channels (except for the outer scenario ring where the RSC are not used). The RSC is determined by the region in which the aircraft finds itself[1].

Consequently when an aircraft switches from one RSC region to the other, it has to switch its VDL Mode 4 message transmissions (10 msg per minute=superframe) to the other RSC[2]. In the case where the aircraft exits from the RSC areas, then it has to increase its transmission rate in the two GSC and cease all RSC transmissions. In either case an aircraft switching transmissions to another channel will have to pick new reservation streams (each message transmitted reserves the corresponding slot at the next superframe, and this is called a reservation stream - if the transmission rate is x msg per minute then there are x reservation streams). Picking a new reservation stream constitutes a garbling risk because the selected slot might be used by another terminal. This risk is dependent on the knowledge the creator of the reservation stream has of reservations by the other stations. The worse case is when an aircraft moves into an RSC region, because then it has to initiate the maximum number of new reservation streams (10 versus a maximum of 6 in the GSC case)[3].

Aircraft entering an RSC region have been listening on its RSC frequency for some time, hence they are supposed to have extensive knowledge of the current reservation table. Evidently the extent of their reservation knowledge will depend among other things on their altitude. They may have missed reservations because they did not receive messages, but it should be noted that a reservation would be lost only if the receiver does not receive the last 4 or more consecutive messages from the same reservation stream. This should therefore be an unlikely event except for stations at far distances whose reception probabilities would be small, or more importantly for stations who are outside LoS (the latter are called hidden terminals).

Aircraft entering an RSC are in a similar to situation to aircraft already in the RSC who have to switch reservation streams to new slots (dithering). According to the VDL Mode 4 SARPs, all reservation streams have to move to new slots every 4-8 superframes. However the new slot has to be pre-announced at least 3 superframes prior to the actual switching. Consequently the main differences between aircraft entering the RSC and aircraft dithering in the RSC are that

a) the former cannot pre-announce their reservations, and

b) the latter (generally) do not have to dither all their reservation streams within the same superframe

In order to mitigate the above garbling risk, the VDL Mode 4 SARPs envisage the use of incremental broadcast to reserve the slot of the next reservation stream as the streams are initiated one by one.

The simulation tool (SPS) used by the TLAT for VDL Mode 4 supports neither aircraft switching transmissions rates nor incremental broadcast. Consequently the impact of the above garbling risk on ADS-B performance could not be measured directly. It was possible however to assess the significance of the risk by looking at the performance of particular aircraft from the TLAT simulation runs.

The transition period when entering an RSC can be expected to last 4 minutes after which the aircraft entering the channel is in exactly the same situation as any other aircraft dithering in the

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[1] Aircraft entering a new area are notified of the channel configuration to use by Directory of Service (DoS) messages broadcasted by ground base stations.

[2] The GSC rate is unchanged (=1msg/min per GSC).

[3] It should also be noted that the two RSC are more heavily loaded than the GSC (~90 versus ~80%).

same RSC. The SPS simulates dithering and from the simulation results one can measure the performance of dithering stations. Consequently the end state of performance after the above 4 minute transition period is known. It will be shown that performance in the beginning of the transition period is not likely to be significantly different.

In a steady state situation knowledge of the RSC reservation table will not change significantly during the 4 minutes of the transition period. The risk of picking a slot used by somebody else will therefore stay the same. At the end of the transition period garbling risk will have been reduced by the fact that the selected slot has been pre-announced 3 times. Any other station(s) using the selected slot should have ceased using that slot, provided they have received at least one of the three pre-announcements made. However hidden terminals cannot receive the pre-announcements and hence garbling risk from them will stay the same. The TLAT simulations discussed in Appendix K.2 have demonstrated that garbling from hidden terminals is the primary factor determining performance. This limiting factor is unchanged in the transition period.

Figure M.3.1 plots for each aircraft within an RSC in one of the TLAT CE2015 simulations the number of reserved slots it has captured at the end of the 30th superframe of the simulation run. This is done by plotting a dot for each aircraft in this RSC using as x-value the altitude of the aircraft and y-value number of reserved slots seen. The 'Number of active slots' line shows the number of active slots at the end of the 30th superframe (=4266 slots).

As it was shown earlier, aircraft that are in high altitudes tend to see the major part of other stations in the RSC, hence they capture also most reservations. For example in the example of Fig. M.3.1 at FL 300 the reserved slots seen ranged between 3941 and 4145 (over 4266 active slots).

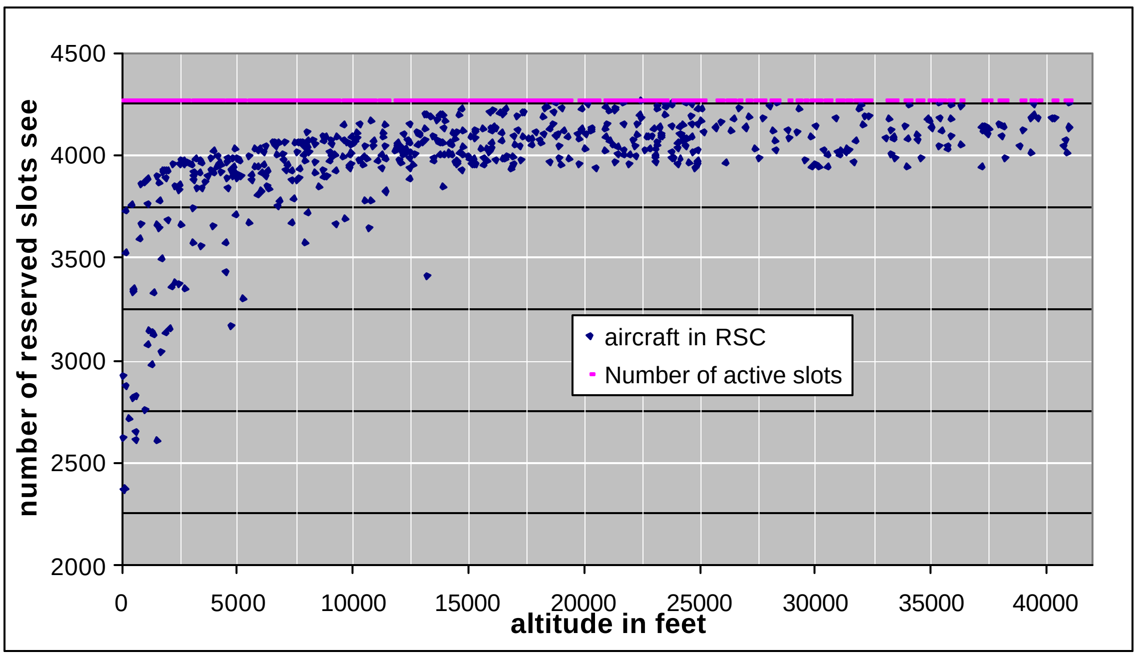


Figure M.3.1 Number of reservations seen by each aircraft in upper RSC

The following figure shows the same chart as the previous slide but only for aircraft on the border of the RSC (semicircle).

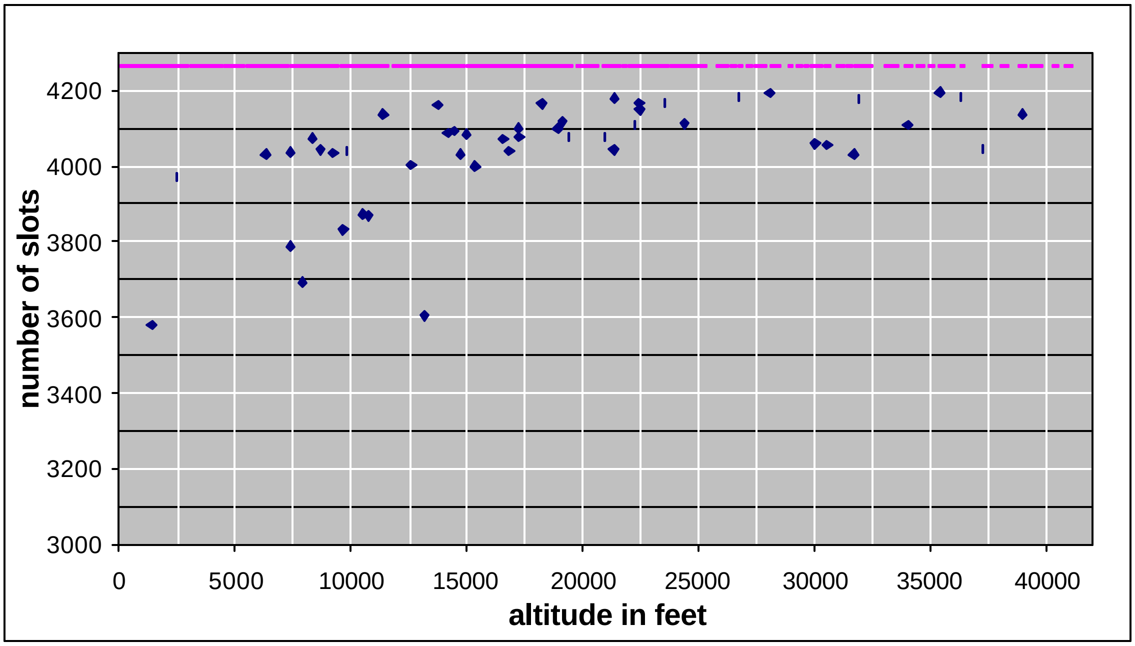


Fig. M.3.2 Reservations seen by aircraft in the periphery of the upper RSC

According to the above figure, a low lying A3 aircraft (FL 11, 82 nmi from Brussels) sees 3580 slots and has to compete with 66 hidden terminals. The probability of selecting a free slot is p_a=(4500-4266)/(4500-3580)=25.4%. After the transition period this probability would become 234/(234+66*10) =26.2%. This difference is minimal and it should have little impact on the reception probability. The measured steady state performance from the selected aircraft (victim receiver at Brussels centre, FL300, 82 nmi) was 74%, and the mean reception probability for all A2/A3 was 85%. This is much higher that the probability of finding a free slot and this happens because reception probability is affected more by the distances of the conflicting targets from the victim receiver than from the number of these targets.

APPENDIX M.4

Availability Considerations for Several ADS-B Avionics Alternatives

M.4.1 Introduction

An important factor when ADS-B is employed as a sole means of ATC surveillance in non-radar airspace is the required system availability. Table 2-4 in the ADS-B MASPS (RTCA DO-242) summarizes system availability requirements for high altitude airspace as Ao = 0.99999; a lower value of Ao = 0.999 is permitted for low altitude operation. Emphasis here is on high altitude operations. Total availability is determined by the aggregate of all components providing the desired air-ground/ground-air ATC service. On the assumption that the aggregate availability level of all other components is an order of magnitude better than the ADS-B avionics alone, we assign the entire 0.99999 budget to the ADS-B avionics configuration for this comparative examination of the relationship between various possible avionics sets and ATC required availability. Several candidate transmit-receive possibilities are compared to this requirement as a function of aircraft mission or flight time.

M.4.2 Alternative Examples

The first example considered assumes dual redundancy for transmit-receive units with single unit Mean Time Between Failure values of 10,000 hours or 20,000 hours to illustrate the effect of MTBF on availability. This is shown in terms of supported aircraft mission time in Figure 1 for the dual units arranged in a hot standby configuration. The availability requirement is met for 30 hour flight times with 10,000 hour MTBFs and is doubled for 20,000 hours. The next example considers the redundant units but with a manual switch over to the backup unit in the event of failure. The plots in Figure 2 assume that a two minute interval is required to recognize the failure and switch to the backup. This lost service time slightly reduces the supported flight time in comparison to a hot standby arrangement.

The next series of examples compare these results to a proposed configuration for 1090 MHz Extended Squitter using redundant transponders for ADS-B broadcast but a single string TCAS receiver with manual switchover to the backup transponder. TCAS experience indicates an MTBF = 13,000 hours. Figure 3 shows this TCAS value combined with dual transponders. The solid curve assumes transponder MTBF = 20,000 hours and a switchover time of 0.05 minutes. The high altitude Ao = 0.99999 requirement is shown as the dashed line near the top of the plot. Clearly this arrangement does not support high altitude availability requirements. To illustrate how the single thread TCAS MTBF determines this result, a transponder MTBF = 1,000 hours and a switchover time of 1 minute was assumed in the dashed curve which differs little from the more realistic solid curve assumptions.

During this study, one TCAS vendor announced that new technology would extend the TCAS MTBF to 40,000 hours. Would this factor of three improvement in MTBF make a significant difference in these results? Although the dashed curve in Figure 4 for this case shows some benefit in comparison to the 13,000 hour baseline previously examined, the results never approach the 0.99999 requirement.

M.4.3 Discussion

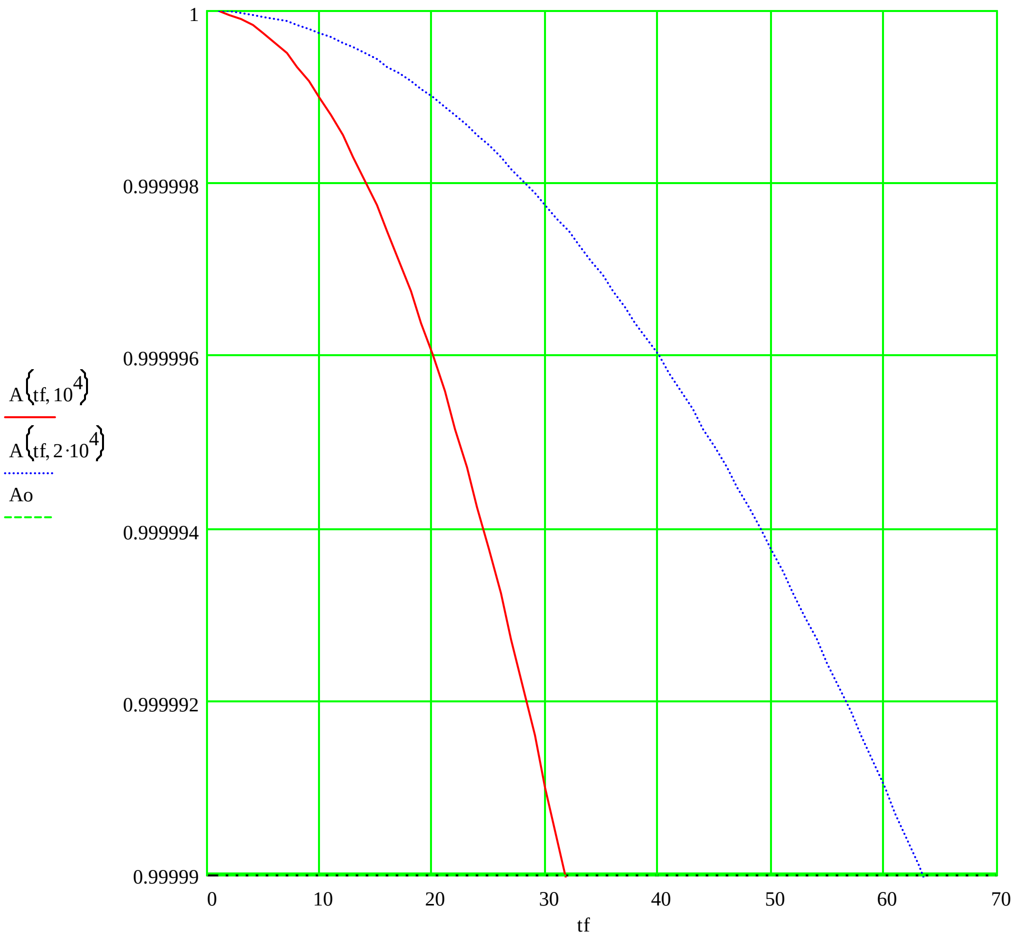
Redundant configurations provide serviceable operational flight times in terms of the high altitude availability requirements even with modest individual unit MTBFs. A configuration employing a single thread TCAS receiver MTBF = 40,000 hours, however, still does not approach the required Ao = 0.99999. More study is required to place these results in an operational context when considering the use of TCAS based ADS-B units in sole means ATC surveillance applications. For example, what is the operational impact of a receiver failure in a pair-wise ADS-B application? Figure 5 shows that if at least one of the pair of aircraft retains an operating receiver and that is operationally acceptable, either assumed TCAS reliability could work. A better understanding of ADS-B failure modes and recovery effects is needed.

For dual redundancy configuration with hot standby in

tf = mission time in hrs   Ao = required system availability

R = unit reliability   mtbf = unit mtbf   High altitude airspace req'd Ao = 0.99999

$R(tf, mtbf) := \exp\left(\frac{-tf}{mtbf}\right)$ $tf := 1, 2 .. 70$ $Ao := 0.99999$ $A(tf, mtbf) := 1 - (1 - R(tf, mtbf))^2$



Dual redundancy hot standby configuration availability vs flight time in hrs for single unit MTBFs of 10,000 hrs (solid curve) and 20,000 hrs (dashed curve). Ao= 0.99999 req'd at high altitude.

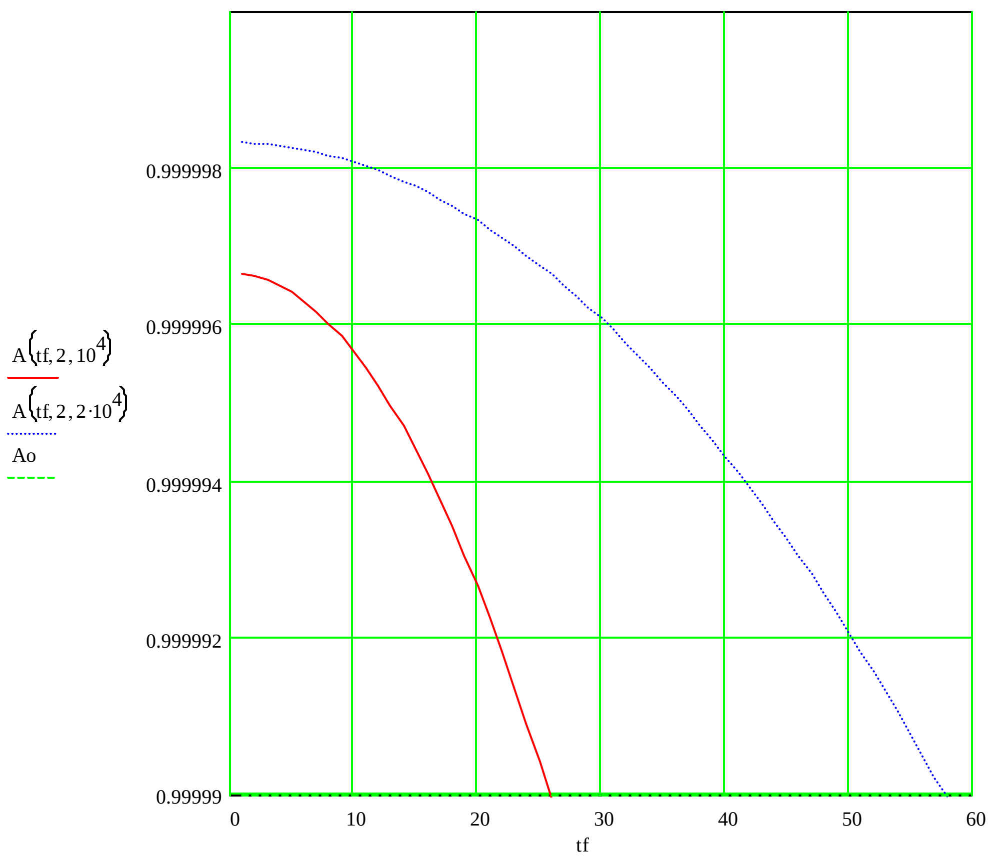
Figure 1

Redundant system with ts minutes for manual service switch over w/unit failure:

Ao = required system availability
mtbf = mean time between unit failures in hrs
tf = flight time in hrs

High altitude req'd Ao = 0.99999 (RTCA DO-242)

$$Ao := 0.99999 \qquad A(tf, ts, mtbf) := \frac{mtbf}{mtbf + \frac{ts}{60}} \cdot \left[1 - (1 - R(tf, mtbf))^2\right] \qquad tf := 1, 2 .. 60$$



Dual redundancy manually switched configuration availability vs flight time in hrs for single unit MTBFs of 10,000 hrs (solid curve) and 20,000 hrs (dashed curve). Assumed switch over time, ts = 2 minuite. Ao= 0.99999 req'd at high altitude.

Figure 2

Redundant modified transponders with ts minutes for manual service switch over w/unit failure for transmit coupled with modified TCAS receiver:

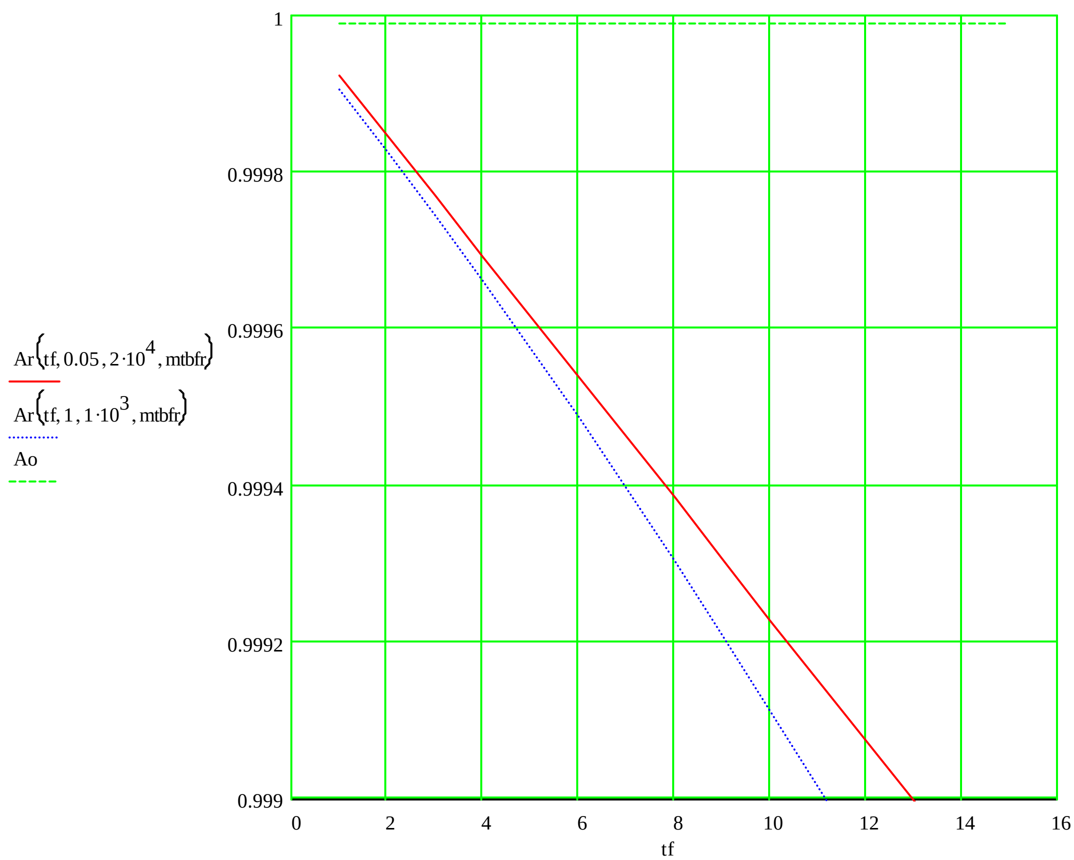
Ao = required system availability
mtbf = mean time between unit failures in hrs
mtbfr = mean time between TCAS failures in hrs
tf = flight time in hrs

High altitude req'd Ao = 0.99999 (RTCA DO-242)

Air-Air req'd Ao = 0.999 (RTCA DO-242)

$tf := 1, 2 .. 15 \qquad ts := 1 \qquad mtbfr := 13000 \qquad Rr(tf, mtbf) := \exp\left(\frac{-tf}{mtbfr}\right) \qquad Rr(1, mtbfr) = 0.99992$

$$Ao := 0.99999 \qquad Ar(tf, ts, mtbf, mtbfr) := \frac{mtbf}{mtbf + \frac{ts}{60}} \cdot \left[1 - (1 - R(tf, mtbf))^2\right] \cdot \exp\left(\frac{-tf}{mtbfr}\right)$$



Dual redundancy manually switched transponder transmit and TCAS receive configuration availability vs flight time in hrs for single transponder unit MTBFs of 20,000 hrs (solid curve) and 1,000 hrs (dashed curve) with TCAS MTBF of 13000 hrs. Assumed switch over time, ts = 0.05 and 1 minuite. Ao= 0.99999 req'd at high altitude.

Figure 3

Redundant modified transponders with ts minutes for manual service switch over w/unit failure for transmit coupled with modified TCAS receiver:

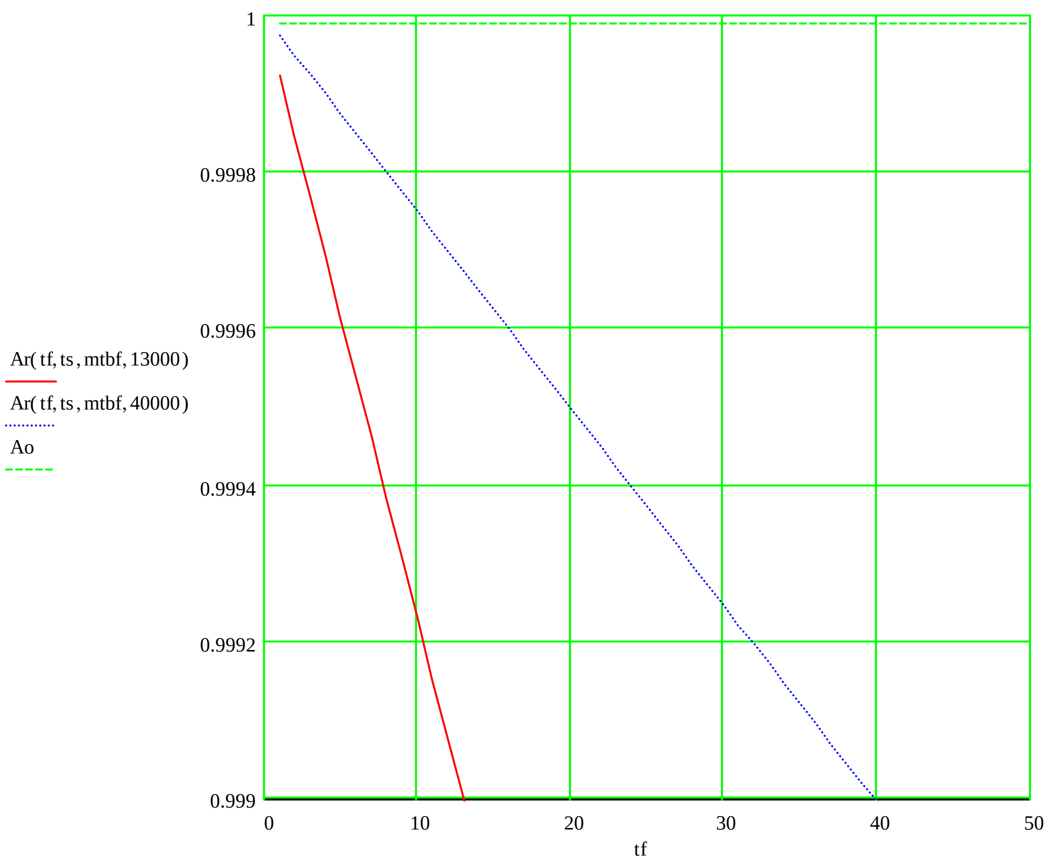
Ao = required system availability
mtbf = mean time between unit failures in hrs
mtbfr = mean time between TCAS failures in hrs
tf = flight time in hrs

High altitude req'd Ao = 0.99999 (RTCA DO-242)

Air-Air req'd Ao = 0.999 (RTCA DO-242)

$tf := 1, 2 .. 50 \qquad ts := 0.05 \qquad mtbf := 20000 \qquad Rr(tf, mtbf) := \exp\left(\frac{-tf}{mtbf}\right) \qquad Rr(1, mtbfr) = 0.99992$

$$Ao := 0.99999 \qquad Ar(tf, ts, mtbf, mtbfr) := \frac{mtbf}{mtbf + \frac{ts}{60}} \cdot \left[1 - (1 - R(tf, mtbf))^2\right] \cdot \exp\left(\frac{-tf}{mtbfr}\right)$$

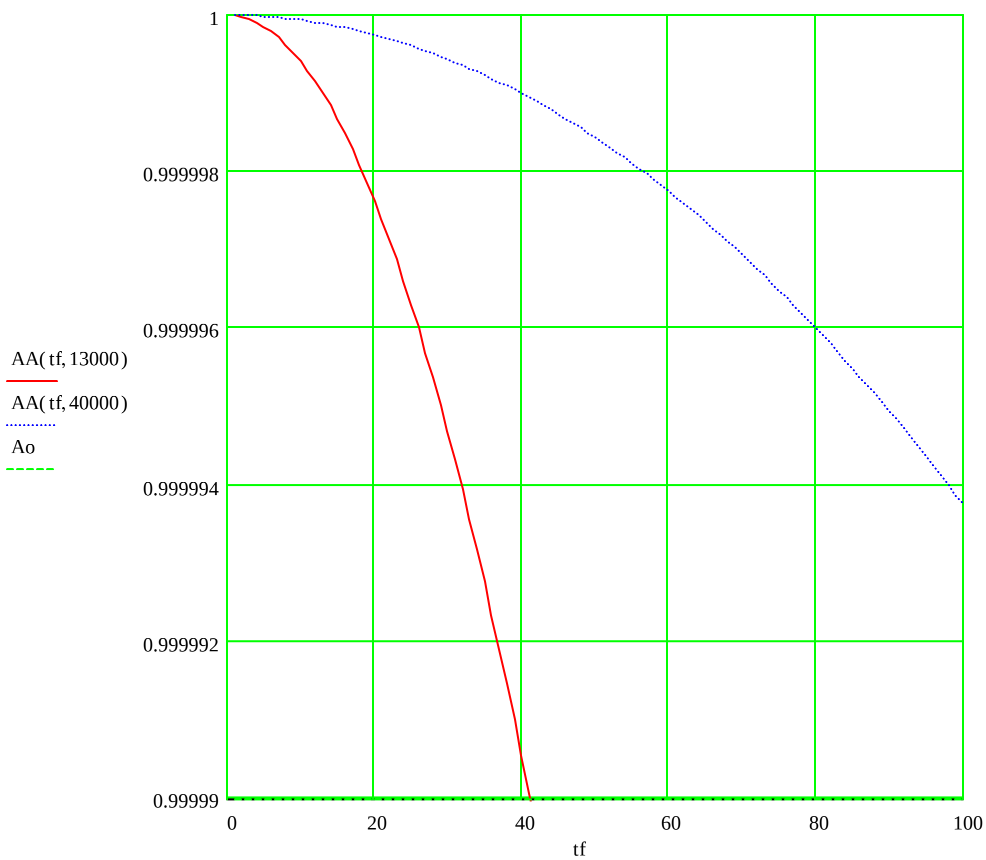


Dual redundancy manually switched transponder transmit and single TCAS receive configuration availability vs flight time in hrs for single transponder unit mtbf = 20,000 hrs with TCAS mtbfr = 13,000 hrs (solid curve)and 40,000 hrs (dashed curve) . Assumed switch over time, ts = 0.05. Ao= 0.99999 req'd at high altitude for ATC. Ao= 0.999 req'd for air-air ADS-B.

Figure 4

$tf := 1, 2 .. 100$

$$Rr(tf, mtbfr) := \exp\left(\frac{-tf}{mtbfr}\right) \qquad AA(tf, mtbfr) := 1 - (1 - Rr(tf, mtbfr))^2 \qquad Ao := 0.99999$$



Availability of at least one of a pair of TCAS receivers for TCAS mtbfr = 13,000 hrs (solid curve)and 40,000 hrs (dashed curve) . Ao= 0.99999 req'd at high altitude for ATC.

Figure 5

Appendix M.5. Projections of 1090 MHz Extended Performance under the 1999 LA Basin Environment

Over a number of years, Lincoln Laboratory developed two simulations for quantitative understanding of Extended Squitter performance in interference. Realizing that omnidirectional reception on aircraft will cause received interference rates to be much higher than the rates for ground based radars, an effort was begun to develop improved reception techniques. The new techniques were developed primarily through a pulse-level simulation. Subsequently a track-level simulation was developed to understand system performance when establishing a new track is an issue. It was deemed difficult to make an analytical assessment of track establishment, because some of the messages that are required to be received are transmitted at a relatively low rate. On the other hand, a long time is available for reception. The problem is that during the time that track acquisition is taking place, air-to-air range is changing, so reception probability is not constant. For these reasons, a straightforward track-level simulation was developed. Following is a description of these two simulations and some performance results.

M.5.1 Formulation of Track-Level Simulation

The track-level simulation is formulated as an encounter between two aircraft flying in opposite directions, both at 600 knots, with a horizontal offset of 5 nmi, as illustrated in Figure M.5-1. In the cases presented in this section, both aircraft are equipped with the highest ADS-B class, A3, and are equipped with applications that transmit and receive intent information, in the form of Trajectory Change Point (TCP) and TCP+1 messages. This is a Monte Carlo simulation in which the encounter is simulated a large number of times, using pseudo random conditions for antenna gain values and other power parameters as well as for interference effects. One aircraft is designated as the transmitting aircraft, and the other as the receiving aircraft. After running a large number of encounters, surveillance performance is assessed by the percentage of encounters for which performance was satisfactory according to the standards given in the RTCA ADS-B MASPS, DO-242.

The simulation includes power deviations resulting from the aircraft antenna gains. In the first case under consideration, both aircraft have antenna diversity. The transmitting aircraft alternates transmission between top and bottom for each type of squitter. The receiving aircraft uses two receivers for simultaneous reception of both antennas. In a case considered subsequently, the receiving aircraft has a single receiver that is switched between the top and bottom antenna. The model used for aircraft antenna gain is the same as the TLAT model, defined in Appendix J.

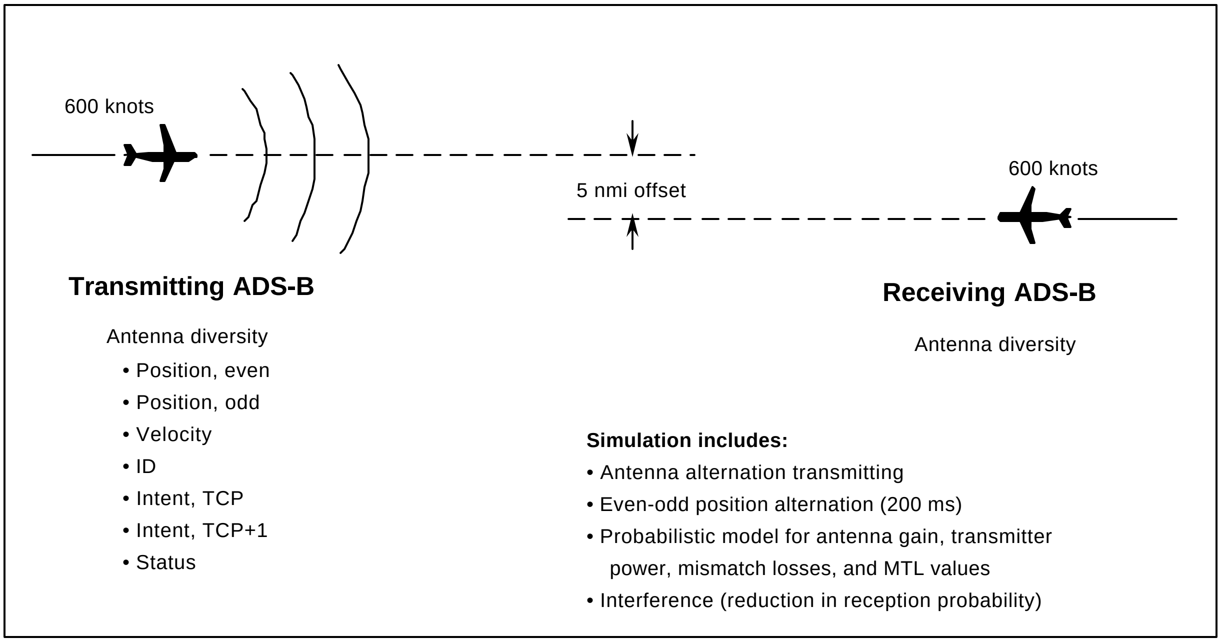


Figure M.5-1. Formulation of the simulation.

In the simulation results that follow, transmitter power and receiver Minimum Triggering Level (MTL) were assigned fixed values. Specifically,

Transmitter power = 51 dBm referred to the antenna

MTL = -84 dBm referred to the antenna

MTL is defined to be the power level for which single squitter reception is 90 percent likely in the absence of interference. Reception probability for weak signals near MTL is modeled by the following formula

$P(C) = 0$	for $z < -6$ dB
$P(C) = 1$	for $z > 3$ dB
$P(C) = 0.9 + 0.072\,z - 0.013\,z^2$	otherwise

where P(C) is the probability of correct reception in the absence of interference, and z is the dB difference between a value of received power and MTL.

$$z = (\text{received power}) - \text{MTL}$$

This formula, which is plotted in Figure M.5-2, is based on bench-test measurements of low-noise Mode S receivers. Interference effects are described below.

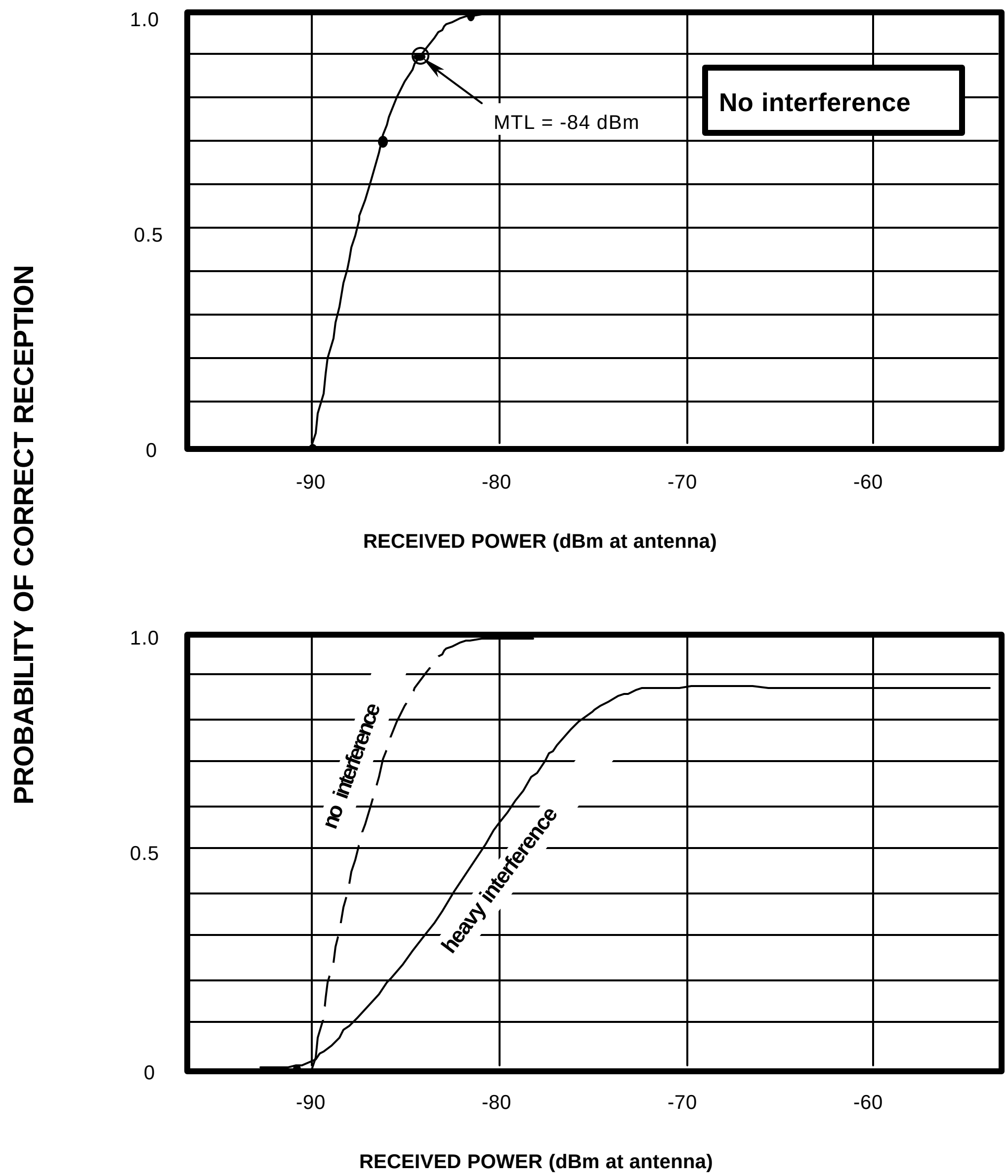


Figure M.5-2. Model for receiver MTL and effects of interference.
(Applicable to the enhanced reception techniques)

The simulation includes seven types of Extended Squitters:

• position-even	(positions transmitted 2/second, alternating even-odd)
• position-odd	(positions transmitted 2/second, alternating even-odd)
• velocity	(transmitted 2/second)
• identification	(transmitted 0.4/second)
• intent, TCP	(transmitted once per 1.7 second)
• intent, TCP+1	(transmitted once per 1.7 second)
• status	(transmitted once per 1.7 second)

The even-odd format bit F is generated in the simulation by a free running clock that alternates between 0 and 1, dwelling at each value for 200 ms. As each squitter is transmitted, the value of F is taken from this clock.

In an environment of high interference, the probability of correct reception is reduced substantially. Based on airborne measurements in the Los Angeles Basin, this effect is modeled as follows.

$$P(C) = \begin{cases} 0 & \text{for } S < -92 \text{ dBm} \\ 0.88 & \text{for } S > -72 \text{ dBm} \\ 0.88 * (0.5 + 1.5\,x - 2\,x^3) & \text{otherwise} \end{cases}$$

where

P(C) is the probability of correct reception

S = received signal power referred to the antenna, and

$x = 0.05 * (S + 82)$

This model is illustrated in Figure M.5-2. The model is applicable to a receiver of 10 MHz bandwidth, using the enhanced Mode S reception techniques, and applies in an interference environment of current conditions in the Los Angeles Basin. The model was derived from the pulse-level simulation, and has been found to be consistent with the airborne measurements in the LA Basin in June 1999 [Reference 17 of Appendix F].

M.5.2 Track Establishment

The simulation can be run to focus just on the performance in establishing a track. This is defined by correct reception of all of the following squitter types:

- position-even
- position-odd
- velocity
- identification
- intent, type A
- intent, type B
- status

Furthermore it is required that both even and odd position messages are received within a 10 second period for track establishment. Using this definition, the simulation was run beginning at 180 nmi air-air range, examining receptions to determine when the track becomes established. After a large number of runs, the probability was determined as the fraction of encounters for which the track was established by the time range reached a given range. Results of this form are accumulated for all values of range, in order to determine performance as a function of range. The simulation results, based on a run of 10,000 encounters, are plotted in Figure M.5-3. In addition to track establishment, the plot also shows performance for communication of intent, which is described below.

In these results, track establishment reaches 95% at a range of 82 nmi. These results apply to the case of a receiving system employing two receivers, and implementing the enhanced reception techniques. Furthermore the results apply to an aircraft installation that includes TCAS, for which TCAS interferes with Extended Squitter reception about 5% of the time. The June 1999 measurements in Los Angeles were made under these conditions, and the per-squitter reception probability model is based on those measurements, so those conditions apply to the results. The simulation can also be run for other cases, as described below.

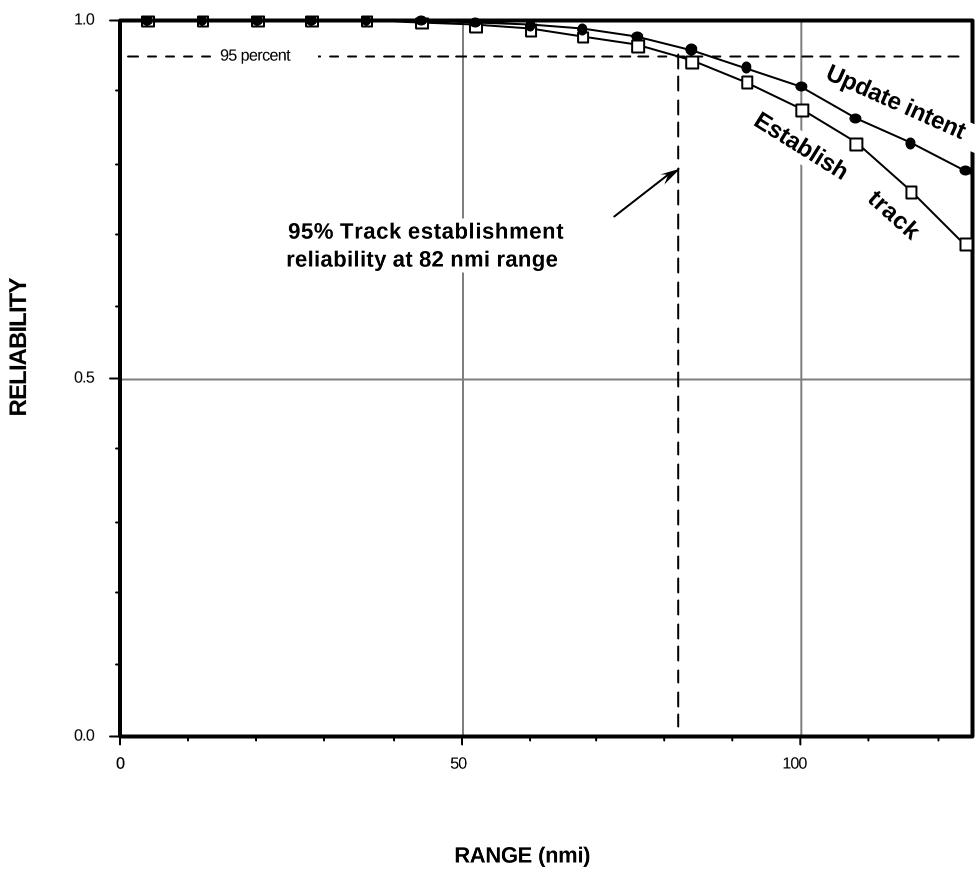


Figure M.5-3. Simulation results showing performance as a function of range.

Note that track establishment as defined requires seven types of messages to all be received, and therefore is substantially more challenging than would be a surveillance-only system. Cases of surveillance-only have also been run in this simulation, and the air-to-air range for track establishment was found to be substantially longer. This behavior is to be expected, especially because of the significantly higher rate with which surveillance information is transmitted.

M.5.3 Updates of Surveillance Information.

For an established track, position and velocity information should be received often enough to keep the track current. For long range air-to-air applications, the ADS-B standards indicate that a surveillance update should occur within 12 seconds with probability 95% and coasts should not exceed 24 seconds with probability 99% (RTCA DO-242, Table 3-4). The simulation has been run to assess surveillance updates relative to these standards. The results in Figure M.5-3 indicate that surveillance performance readily satisfies the RTCA ADS-B MASPS standards after track establishment has occurred.

M.5.4 Communication of Intent Information

Intent information (TCP and TCP+1) transmitted air-to-air tends to be constant for long periods of time, and therefore updates are not needed as often as surveillance updates. Occasionally, however, intent information changes, and after a change, the information should be received at the other aircraft without excessive delay. Specifically, the RTCA ADS-B MASPS requires that for long range air-to-air applications, after a change in intent, the new information should be received within 24 seconds with probability 0.95 (RTCA DO-242, Table 3-4, Note 8).

The simulation was run to assess the updating of intent after a change. The probability of full intent reception (both TCP and TCP+1) within 24 seconds is shown in Figure 3, along with the track establishment results. These results were obtained from a simulation run of 10,000 encounters.

These results can be summarized by saying that the intent communication performance is nearly the same as the track establishment performance. There is a slight consistent difference, in the sense that track establishment is the more challenging condition.

M.5.5 Other Cases

Similar results have been obtained for a number of other cases, involving different avionics configurations and different receiver designs. The results plotted in Figure M.5-4 summarize performance as affected by several design differences, including (1) use of current reception techniques instead of the enhanced techniques, (2) use of a single receiver switched between the top and bottom antennas, and (3) different values of blanking caused by TCAS. In the cases involving current reception techniques, use of a conservative error correction technique is included in order to keep the rate of undetected errors very low.

Receiver blanking, which prevents reception of Extended Squitter signals can occur during the interrogations transmitted by TCAS. Although the interrogations are transmitted at a different frequency (1030 MHz), they interfere with Extended Squitter receptions (1090 MHz) because of the much higher power level. Additional blanking can be caused by the replies to TCAS interrogations. For a combination TCAS and ADS-B built together in one unit, additional blanking may be caused if Extended Squitter reception is not activated during the times between TCAS interrogations.

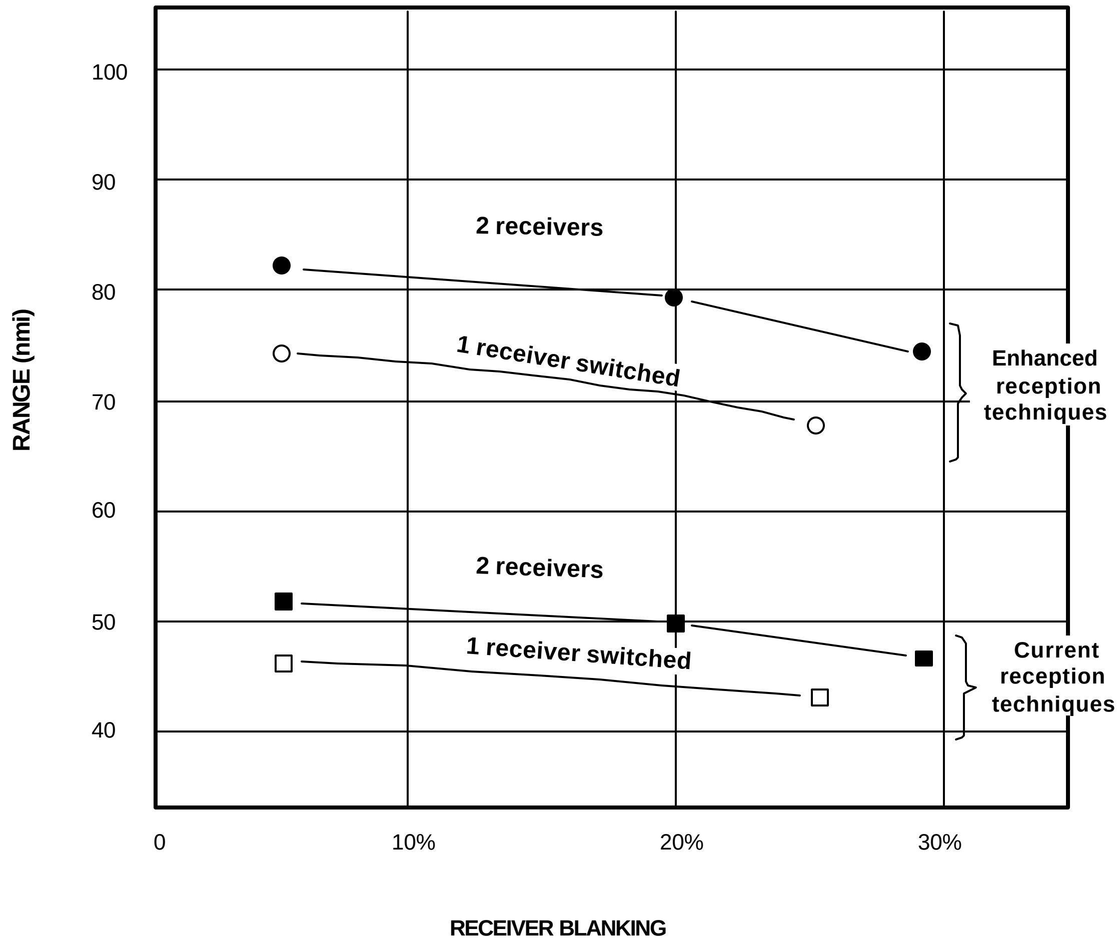


Figure M.5-4. Air-air performance of Extended Squitter, simulation results.

Notes. (1) The "current reception techniques" include a conservative form of error correction.
(2) These results apply in a high interference environment.
(3) These results indicate the 95 percentile ranges; substantial performance exists at greater ranges.
(4) These results include intent communications; surveillance is reliable to greater ranges.
(5) These results apply to a minimum power transponder (51 dBm), most targets will have longer ranges.

M.5.6 System Performance Envelope

The results described above indicate that the air-to-air range for reliable surveillance and intent communication is affected by interference. The reduction in range can be shown explicitly as a function of interference level in the form of a system performance envelope, as in Figure M.5-5. The horizontal scale, indicating level of interference, is normalized to the level measured in the Los Angeles Basin in June 1999. Quantitatively, this is primarily an ATCRBS fruit rate of 10,000 replies per second above -80 dBm and 19,000 replies per second above -85 dBm (referred to the antenna). It is clear from Figure M.5-5 that this level of interference causes air-to-air range to decrease relative to the range expected in oceanic and low-density enroute environments. Higher levels of interference would cause additional degradation as indicated in the figure. As noted in the figure, these results apply under certain worst-case conditions, and that consistently longer range performance is to be expected under more typical conditions.

Additional results in this form are plotted in Figure M.5-6. This figure provides a comparison between the most effective and the least effective reception techniques, referring to the combinations shown in Figure 4 above. The least effective techniques include (a) one receiver switched between the top and bottom antennas, (b) blanking of 20% caused by TCAS operations on the receiving aircraft, and (c) current reception techniques.

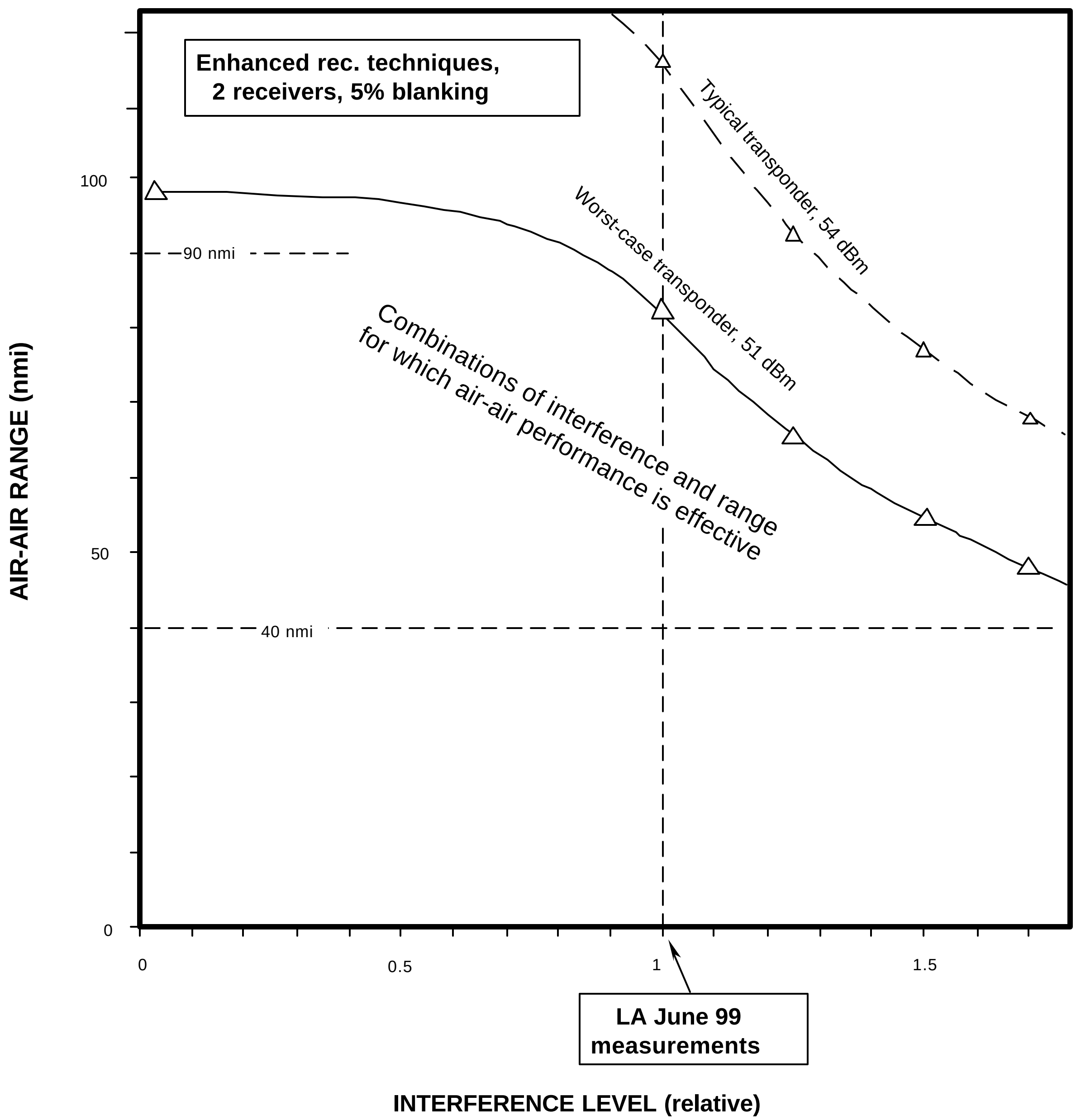


Figure M.5-5. System performance envelope, showing how air-air range is affected by interference

Notes. (1) These results include intent communications; surveillance is reliable to greater ranges.
(2) These results apply to a minimum power transponder (51 dBm), most targets will have longer ranges.
(3) These results indicate the 95 percentile ranges; substantial performance exists at greater ranges.

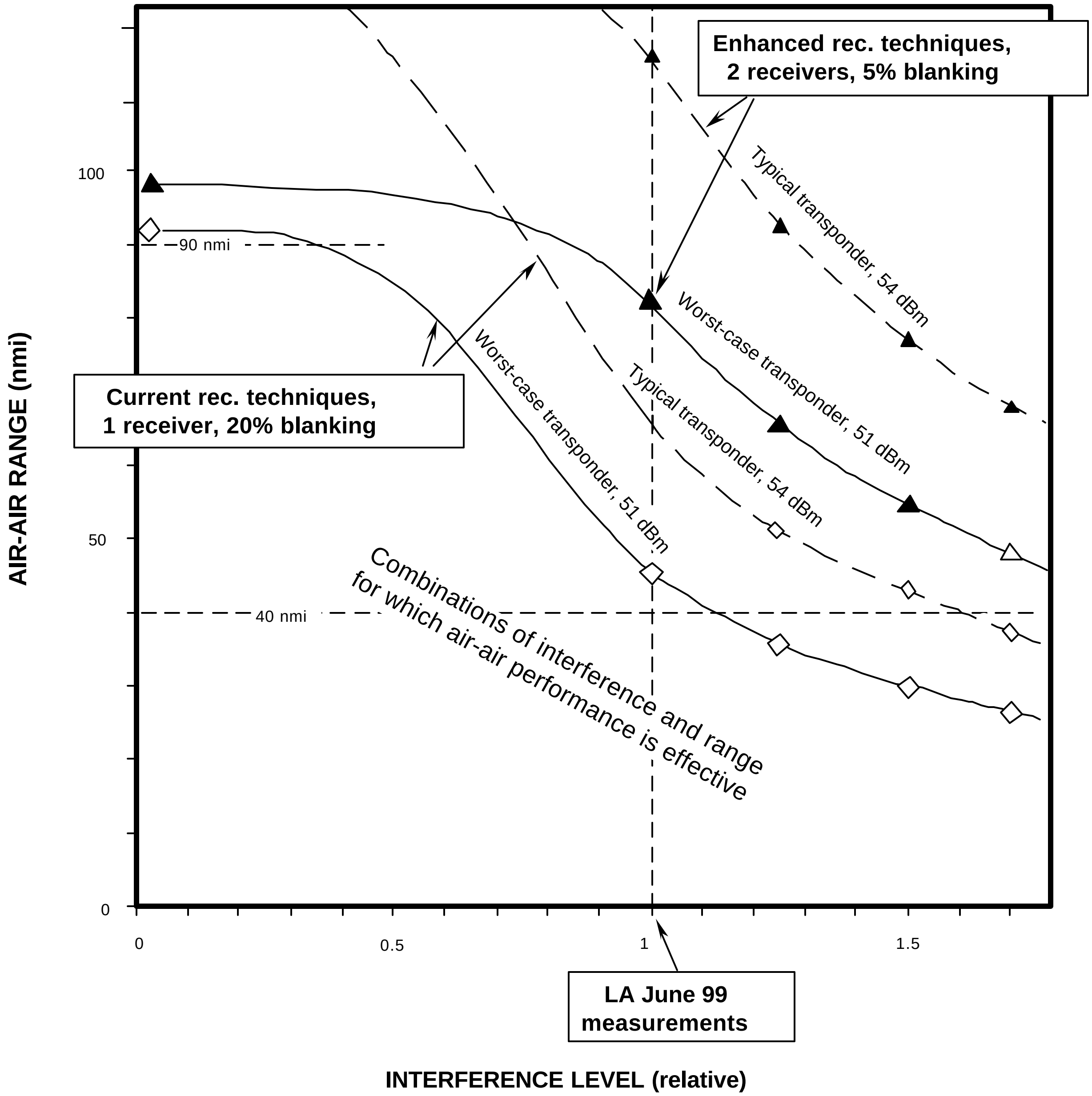


Figure M.5-6. System performance envelopes for different receiver configurations.

Notes. (1) The “current reception techniques include a conservative form of error correction.
(2) These results include intent communications; surveillance is reliable to greater ranges.
(3) These results apply to a minimum power transponder (51 dBm), most targets will have longer ranges.
(4) These results indicate the 95 percentile ranges; substantial performance exists at greater ranges.

APPENDIX M.6

RECEIVED SIGNAL LEVELS AND SIGNAL-TO-MULTIPATH ESTIMATES

1.0 INTRODUCTION

Effects of antenna gain pattern variations on received signal levels and multipath behavior at L-band and VHF are examined. Received signal levels and elevation plane multipath levels are calculated in section 2.0 for two aircraft at altitudes of a feet and h feet in a closing approach scenario and separated by a distance, D nm. Top and bottom elevation plane aircraft antenna patterns as well as an approximation to average ground surface reflectivity are used to estimate the effect of these factors on link budget signal levels and relative multipath levels. The relative time delay of the multipath signal in microseconds (usec) is shown for signal-to-multipath ratios (SMR) less than 10 dB. Only stationary multipath is considered since the objective here is to examine performance sensitivity to these factors. Attention is focused in all cases on identification of circumstances of interest for further investigation.

Section 3.0 calculates received signal level as a function of separation range for an aircraft in level flight at an altitude of “a” feet approaching a ground antenna at a height “h” feet above the reflecting surface with a specified gain pattern. Elevation plane received signal fading is shown for both top and bottom aircraft antennas.

Section 4.0 estimates the variation in horizontal plane SMR for a specified relative delay in multipath and a flat plate reflector at various locations relative to the transmitter and receiver. Results are summarized in Section 5.0. The document format is in the form of an annotated Mathcad program.

2.0 AIR-to-AIR RECEIVED SIGNAL LEVELS and SIGNAL-to-MULTIPATH RATIO (SMR)

2.1 Surface Reflectivity

Air-to-air signal reception estimates begin with an empirical approximation to average ground or water surface reflectivity for vertical polarization. Adaptation of this term for rough surfaces uses the standard radar model for a mean surface height variation. The plots are in terms of the incident angle measured from the reflecting surface. From Figure 2-1, the example given here in Figure 2-2 is for average ground with a mean surface height variation of 1 foot and a frequency of 1090 MHz. At an 8 foot VHF wavelength, the rough surface model in Figure 2-2 approaches the smooth ground surface (solid curve) of Figure 2-1.

Reflection Coefficient Model for Brewster angles $\psi w := 5$ (water) $\psi g := 15$ (ground)

Fresnel water reflection coefficient, $\rho\omega$, vs elevation angle, ψ: $\psi := 0.1, 0.15 .. 90$

$$\rho w(\psi) := 0.7\cdot\exp\left[-\left(\frac{\psi}{\psi w - 4}\right)^2\right] + 0.8\cdot\exp\left[-\left(\frac{\psi - 90}{90}\right)^2\right] \qquad \beta w(\psi) := \mathrm{if}(\psi < \psi w, \pi, 0)$$

Fresnel ground reflection coefficient, ρg, vs elevation angle, ψ:

$$\rho 1(\psi) := \cos\left(\frac{\psi}{\psi g}\cdot\frac{\pi}{2}\right) \qquad \rho 2(\psi) := 0.6\cdot\cos\left(\frac{\psi - 90}{90 - \psi g}\cdot\frac{\pi}{2}\right) \qquad \rho g(\psi) := \mathrm{if}(\psi \le \psi g, \rho 1(\psi), \rho 2(\psi))$$

$$\beta g(\psi) := \mathrm{if}(\psi < \psi g, \pi, 0)$$

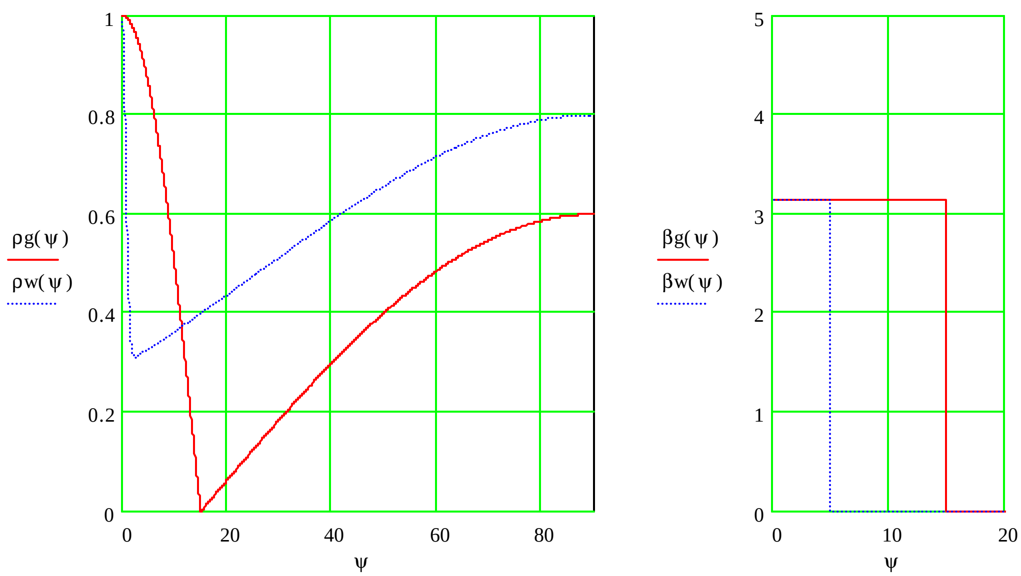


Figure 2-1 Reflection coefficient and phase angle for average ground and water vs elevation angle

Rough surface reflection coefficient,m, for wavelength,λ, and mean surface height,δ:

$\rho o = \rho w$ or ρg $\qquad \rho o(\psi) := \rho g(\psi) \qquad \beta o(\psi) := \beta g(\psi)$

$$F := 1090 \qquad \lambda := \frac{984}{F} \qquad \lambda = 0.903 \qquad k := \frac{2 \cdot \pi}{\lambda} \qquad \delta := 1$$

$$m(\delta, \psi) := \rho o(\psi) \cdot \exp\left[-2 \cdot k^2 \cdot \delta^2 \cdot \sin\left(\frac{\psi}{57.3}\right)^2\right] \qquad M(\delta, \psi) := 20 \cdot \log(m(\delta, \psi))$$

$F = 1090 \qquad \delta = 1 \qquad \rho g(\psi) \qquad \beta g(\psi)$

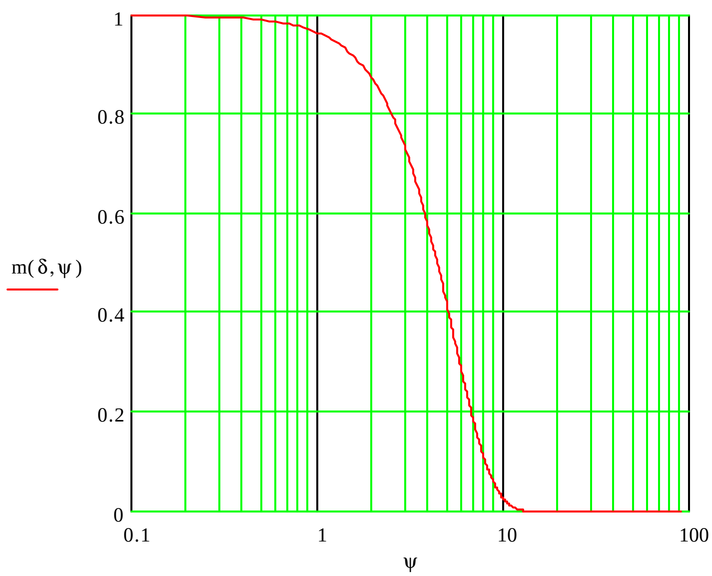


Figure 2-2 Rough surface ground relection coefficient for 1090 Mhz and surface rms value of 1 ft

2.2 Top and bottom aircraft antenna elevation plane patterns

The elevation angle discussed above for surface reflectivity is the surface grazing angle. Antenna gain patterns are expressed in terms of the depression angle from the aircraft horizontal plane; this is equal to the grazing angle for assumed level flight. The following parametric expressions of top and bottom antenna gain variation are representative of typical aircraft blade antenna patterns with 0 dBi gain in the horizontal plane and peak gain of about 4 dBi. Actual patterns display variations about these values, but these approximations support our current interests. The parameters may be adjusted to approximate gains for other antenna locations providing higher or lower gains in the vicinity of the horizon. Experience shows, for example, that considerably lower gains in the forward direction can result with antennas located towards the rear of the aircraft. Available data for large aircraft indicate no significant differences in patterns at L-band and VHF.

Bottom Mounted Aircraft Antenna Gain in dBi, Gbd, vs elevation angle, α:

$\theta a := 44 \qquad \theta p := 26 \qquad \alpha := -90, -89 .. 90 \qquad \eta := 1$

$$Gb(\alpha) := \left(\frac{2}{\frac{\theta a}{57.3}} \cdot \eta\right)^{0.5} \cdot \exp\left[-\left(1.174 \cdot \frac{\alpha - \theta p}{\theta a}\right)^2\right] \qquad Gbd(\alpha) := 20 \cdot \log(Gb(\alpha))$$

$Gbd(0) = 0 \qquad Gbd(\theta p) = 4.2$

Top Mounted Aircraft Antenna Gain in dBi, Gtd, vs elevation angle, α:

$\theta a := 44 \qquad \theta p := -26 \qquad \alpha := -90, -89 .. 90 \qquad \eta := 1$

$$Gt(\alpha) := \left(\frac{2}{\frac{\theta a}{57.3}} \cdot \eta\right)^{0.5} \cdot \exp\left[-\left(1.174 \cdot \frac{\alpha - \theta p}{\theta a}\right)^2\right] \qquad Gtd(\alpha) := 20 \cdot \log(Gt(\alpha))$$

$Gtd(0) = 0 \qquad Gtd(\theta p) = 4.2$

$Gtd(0) = 0 \qquad Gbd(0) = 0$

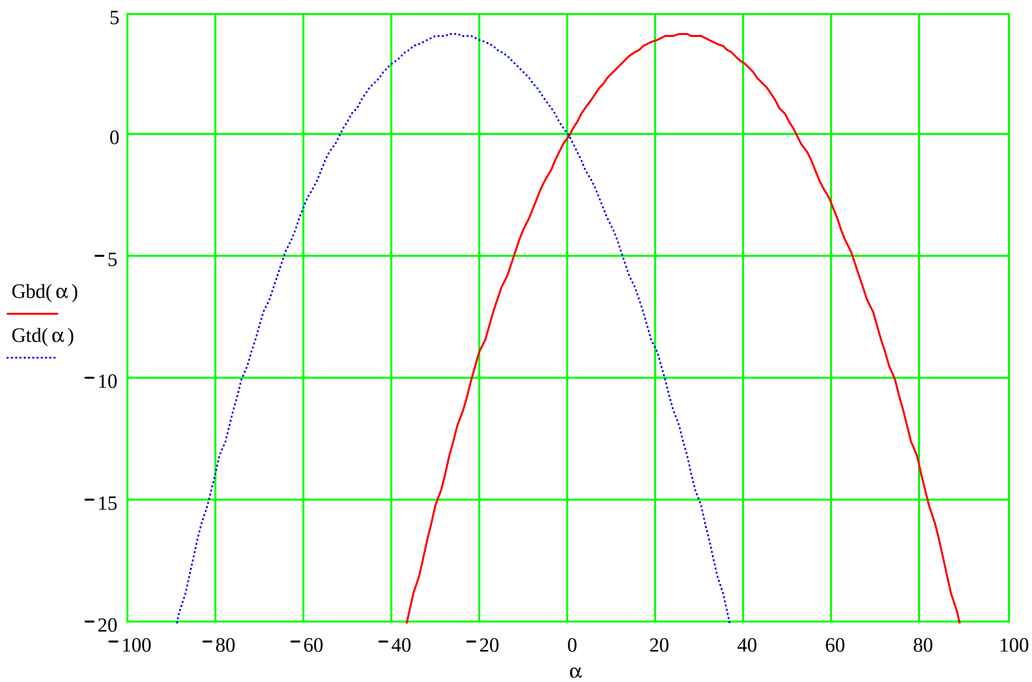


Figure 2-3 Bottom antenna pattern (solid) and top antenna pattern (dashed) vs depression angle

2.3 Air to Air Geometry with Elevation Plane Multipath

Direct air-air aspect angles and multipath reflection angles for aircraft separated by D nm and at altitudes a and h are given below along with the difference in slant range and the relative delay in the multipath signal. Figure 2-4 illustrates the variations in the direct angle and the reflected angle as a function of separation distance for one aircraft at 8000 feet and the other at 12000 feet. Notice the slow change in the direct angle in this case until the separation is less than 20 nm.

Plane Earth Link Geometry $\quad a \ge h$

$$a := 12000 \quad h := 8000 \quad Dmax := 1.23\left(\sqrt{h}+\sqrt{a}\right) \quad Dmax = 245 \quad d(D) := D \cdot 6000$$

$$\psi r(a,h,D) := \operatorname{atan}\left(\frac{a+h}{d(D)}\right) \quad \psi(a,h,D) := 57.3 \cdot \psi r(a,h,D) \quad r(a,h,D) := \left[d(D)^2 + (a+h)^2\right]^{\frac{1}{2}}$$

$$\alpha r(a,h,D) := \operatorname{atan}\left(\frac{a-h}{d(D)}\right) \quad \alpha(a,h,D) := 57.3 \cdot \alpha r(a,h,D) \quad l(a,h,D) := \left[d(D)^2 + (a-h)^2\right]^{\frac{1}{2}}$$

$$\Delta(a,h,D) := \frac{(r(a,h,D) - l(a,h,D))}{984}$$ Delay in μsec $\quad D := 1, 1.5 .. 100$

Direct angle, α, and Elevation angle, ψ, vs distance, D, for altitudes, h and a:

$a = 12000 \quad h = 8000 \quad Dmax = 245$

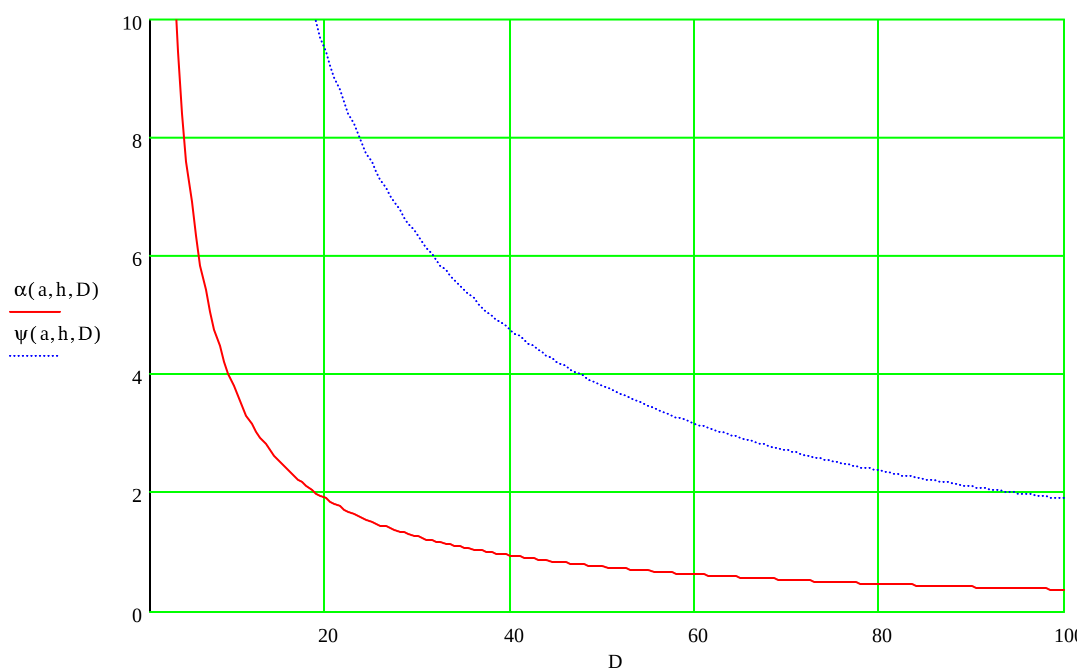


Figure 2-4 Variation of depression angle and grazing angle with separation distance for indicated values of altitudes, a and h

2.4 Transmit-Receive Antenna Gain Products

Transmit-receive antenna gain products as a function of aircraft separation geometry and assumed top and bottom antenna patterns are determined below for the various combinations of direct and reflected signals. Symmetrical antenna configurations are assumed on both aircraft.

Product of bottom-bottom aircraft antenna gains vs distance,D, for direct link:

$$GBBD(a,h,D) := Gbd(\alpha(a,h,D)) + Gbd(-\alpha(a,h,D))$$

Product of bottom-bottom aircraft antenna gains vs distance,D, for reflected link:

$$GBBR(a,h,D) := Gbd(\psi(a,h,D)) + Gbd(\psi(a,h,D))$$

Product of top-top aircraft antenna gains vs distance,D, for direct link:

$$GTTD(a,h,D) := Gtd(\alpha(a,h,D)) + Gtd(-\alpha(a,h,D))$$

Product of top-top aircraft antenna gains vs distance,D, for reflected link:

$$GTTR(a,h,D) := Gtd(\psi(a,h,D)) + Gtd(\psi(a,h,D))$$

Product of bottom-top aircraft antenna gains vs distance,D, for direct link:

$$GBTD(a,h,D) := Gbd(\alpha(a,h,D)) + Gtd(-\alpha(a,h,D))$$

Product of bottom-top aircraft antenna gains vs distance,D, for reflected link:

$$GBTR(a,h,D) := Gbd(\psi(a,h,D)) + Gtd(\psi(a,h,D))$$

$Gtd(0) = 0$ $\quad$ $Gbd(0) = 0$ $\quad$ $a = 12000$ $\quad$ $h = 8000$ $\quad$ $Dmax = 245$

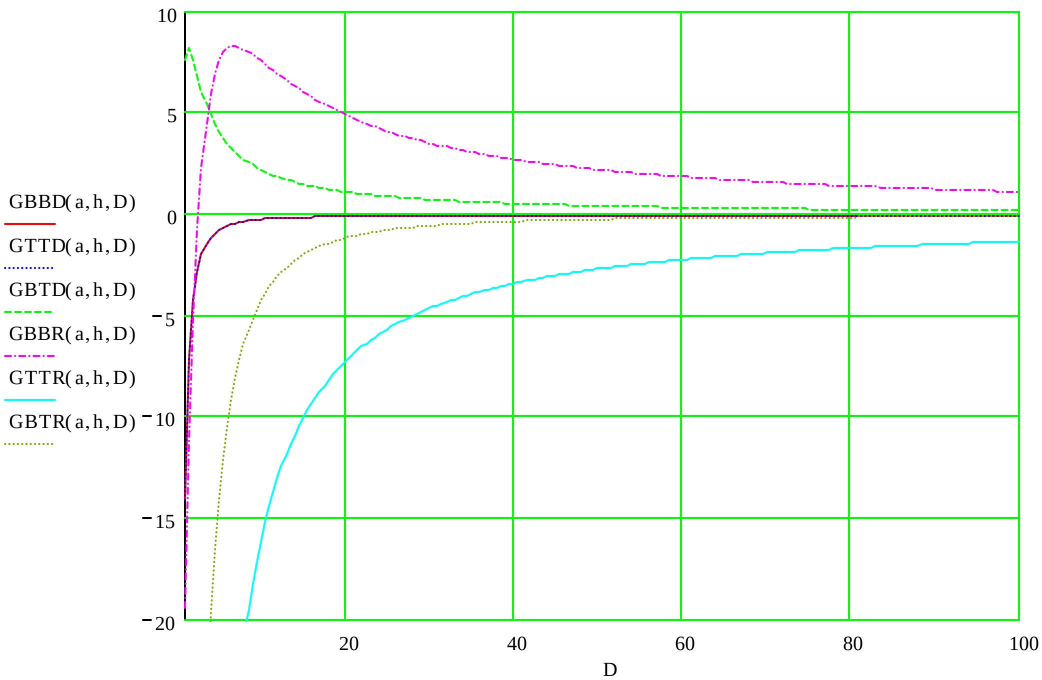


Figure 2-5 Antenna gain products vs separation geometry for direct and mutipath signals

2.5 Link Budget Characteristics

Having expressions of antenna gain products as a function of separation geometry, received signal levels including antenna gain factors for combinations of top/bottom antennas as well as free space loss can be compared with values usually obtained with the assumption of constant 0 dBi antenna gains. Power in dBm at the transmit antenna is given by Ptd. Feed line loss in dB between the receive antenna and the receiver is Ld, and the receiver is described by a 90% MTL probability of decode given in dBm.

Received signal level in dBm as a function of distance,l, in nmi: $\mathrm{Ptd} := 30 + 10 \cdot \log(250)$

$\mathrm{Ptd} = 54 \qquad \mathrm{Ld} := 0 \qquad \mathrm{MTL}(D) := -84 \qquad D := 1, 1.5 .. 150$

$$\mathrm{PBBD}(a, D, h, \lambda) := (\mathrm{Ptd} + \mathrm{GBBD}(a, h, D)) - \left[37.5 + \left\{20 \cdot \log\left(\frac{l(a, h, D)}{6000}\right) + 20 \cdot \log\left(\frac{984}{\lambda}\right)\right\}\right] - \mathrm{Ld}$$

$$\mathrm{PTTD}(a, D, h, \lambda) := (\mathrm{Ptd} + \mathrm{GTTD}(a, h, D)) - \left[37.5 + \left\{20 \cdot \log\left(\frac{l(a, h, D)}{6000}\right) + 20 \cdot \log\left(\frac{984}{\lambda}\right)\right\}\right] - \mathrm{Ld}$$

$$\mathrm{PBTD}(a, D, h, \lambda) := (\mathrm{Ptd} + \mathrm{GBTD}(a, h, D)) - \left[37.5 + \left\{20 \cdot \log\left(\frac{l(a, h, D)}{6000}\right) + 20 \cdot \log\left(\frac{984}{\lambda}\right)\right\}\right] - \mathrm{Ld}$$

$$\mathrm{P00D}(a, D, h, \lambda) := (\mathrm{Ptd} + 0) - \left[37.5 + \left\{20 \cdot \log\left(\frac{l(a, h, D)}{6000}\right) + 20 \cdot \log\left(\frac{984}{\lambda}\right)\right\}\right] - \mathrm{Ld}$$

These assumptions for a 1090 MHz Extended Squitter power of 250 watts (54 dBm) at the antenna, no receiver loss (Ld = 0) and a receiver MTL = -84 dBm yield the received signal level curves for different top/bottom antenna pairs shown in Figure 2-6. The indicated MTL range is about 100 nm in this case. Notice the best pairing in this example, PBTD, or bottom transmit/top receive, differs only slightly from the reference, P00D, until the separation is less than about 5 nm. This is due to the assumed gains near 0 dBi in the vicinity of the horizon and the 4,000 foot altitude difference in this example. Also, notice the worst combination, bottom/bottom (PBBD), shows a link fade at short ranges, but the faded signal is still well above MTL due to the short slant range in this case. Other assumptions and flight configurations can, of course, produce different results.

Link fade behavior for UAT at 981 MHz is similar to that of 1090 MHz except the MTL sensitivity range is about 170 nm for Ptd = 50 dBm and a receiver MTL = -92 dBm. The non-interference limited range for VDL Mode 4 at 118 MHz with Ptd = 40 dBm and an MTL = -98 dBm is hundreds of miles and a practical limit is just that imposed by the nominal line of sight (LOS) range of 245 nm in this case. As a general observation, we may note that a 20 dB fade at a 10 nm slant range results in a signal level equivalent to that generally experienced for a co-altitude separation of 100 nm. From that point of view, VDL Mode 4 has the greatest fade margin, followed by UAT, then 1090 MHz Extended Squitter

Gtd(0) = 0   Gbd(0) = 0   F = 1090   Ptd = 54   Ld = 0   a = 12000   h = 8000   Dmax = 245

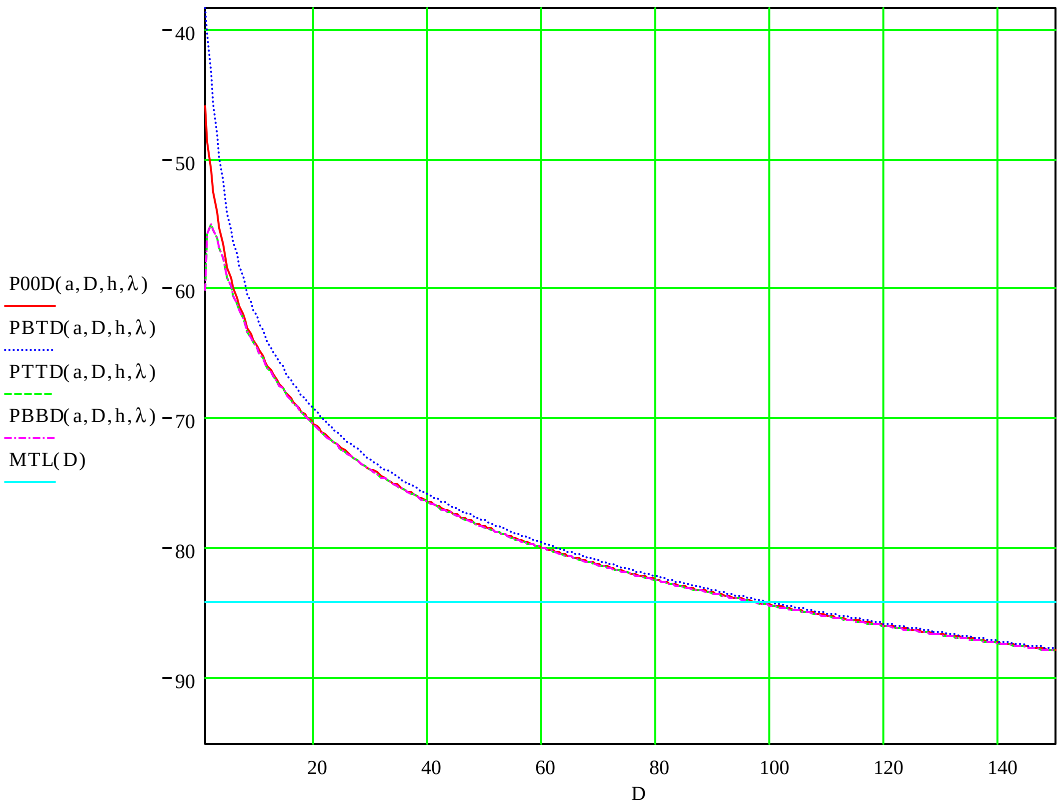


Figure 2-6 Received signal level in dBm vs separation, D, in nm for the indicated link and altitude parameters. The 0 dBi antenna gain reference is showm as P00D.

2.6 Air-to-Air Elevation Plane Multipath

Direct and ground reflected multipath signal levels are computed below for F = 1090 MHz, the rough surface reflection coefficient given in Figure 2-2, the top / bottom transmit and receive antenna patterns given in Figure 2-3, and flight altitudes of a and h. The resulting ratio of direct-to-multipath signal levels in dB, SMR, are shown in Figure 2-7(a) for a = 12000 ft and h = 8000 ft. Relative time delay (usec) in the multipath signal is plotted in Figure 2-7(b) over the separation range for SMRbb < 10 dB. UAT at 981 MHz shows multipath characteristics similar to Figure 2-7(b). Both 1090 MHz Extended Squitter and UAT experience very low SMR ratios at longer ranges in this example (particularly for the bottom/bottom antenna pair) and some decoding problems may be experienced with the associated multipath relative delay of fractions of a microsecond.

Multipath behavior for VDL Mode 4 at 118 MHz with the assumed 1 foot surface height variation is somewhat different than that at L-band. Figure 2-8 indicates higher multipath levels at high elevation angles at VHF since the assumed surface roughness height of 1 foot in this example is nearly smooth in terms of the 8 foot VHF wavelength. Relative delays in multipath of on the order of microseconds are shown in the lower part of the figure (the discontinuity in the delay curve is due to the plot constraint of only showing delay for SMR < 10 dB). These delays will also have a different potential impact on performance for L-band and VHF channel rates. With a VDL Mode 4 bit length of 50 usec, multipath delays on the order of microseconds are more likely to signal level modification than decode errors as would be the case for the nominal 1 Mb/s channel rates for 1090 MHz Extended Squitter and UAT.

Signal-multipath ratio for bottom-bottom antenna pairs, SMRbb:

$$\mathrm{DBB}(a,D,h,\lambda) := \mathrm{GBBD}(a,h,D) - \left[37.5 + \left(20\cdot\log\left(\frac{l(a,h,D)}{6000}\right) + 20\cdot\log\left(\frac{984}{\lambda}\right)\right)\right]$$

$$\mathrm{RBB}(a,D,h,\lambda) := \mathrm{GBBR}(a,h,D) - \left[37.5 + \left(20\cdot\log\left(\frac{l(a,h,D)}{6000}\right) + 20\cdot\log\left(\frac{984}{\lambda}\right)\right)\right] + 20\cdot\log(m(\delta,\psi(a,h,D)))$$

$$\mathrm{SMRbb}(a,D,h,\lambda) := \mathrm{DBB}(a,D,h,\lambda) - \mathrm{RBB}(a,D,h,\lambda)$$

Signal-multipath ratio for top-top antenna pairs, SMRtt:

$$\mathrm{DTT}(a,D,h,\lambda) := \mathrm{GTTD}(a,h,D) - \left[37.5 + \left(20\cdot\log\left(\frac{l(a,h,D)}{6000}\right) + 20\cdot\log\left(\frac{984}{\lambda}\right)\right)\right]$$

$$\mathrm{RTT}(a,D,h,\lambda) := \mathrm{GTTR}(a,h,D) - \left[37.5 + \left(20\cdot\log\left(\frac{l(a,h,D)}{6000}\right) + 20\cdot\log\left(\frac{984}{\lambda}\right)\right)\right] + 20\cdot\log(m(\delta,\psi(a,h,D)))$$

$$\mathrm{SMRtt}(a,D,h,\lambda) := \mathrm{DTT}(a,D,h,\lambda) - \mathrm{RTT}(a,D,h,\lambda)$$

Signal-multipath ratio for bottom-top antenna pairs, SMRbt:

$$\mathrm{DBT}(a,D,h,\lambda) := \mathrm{GBTD}(a,h,D) - \left[37.5 + \left(20\cdot\log\left(\frac{l(a,h,D)}{6000}\right) + 20\cdot\log\left(\frac{984}{\lambda}\right)\right)\right]$$

$$\mathrm{RBT}(a,D,h,\lambda) := \mathrm{GBTR}(a,h,D) - \left[37.5 + \left(20\cdot\log\left(\frac{l(a,h,D)}{6000}\right) + 20\cdot\log\left(\frac{984}{\lambda}\right)\right)\right] + 20\cdot\log(m(\delta,\psi(a,h,D)))$$

$$\mathrm{SMRbt}(a,D,h,\lambda) := \mathrm{DBT}(a,D,h,\lambda) - \mathrm{RBT}(a,D,h,\lambda)$$

Relative delay of multipath signal in usec for SMRbb < 10 dB:

$$\Delta(a,h,D) := \frac{(r(a,h,D) - l(a,h,D))}{984}$$

$$M(a,h,D) := \mathrm{if}(\mathrm{SMRbb}(a,D,h,\lambda) < 10, \Delta(a,h,D), 0)$$ Delay in μsec

F = 1090 δ = 1 Gtd(0) = 0 Gbd(0) = 0 a = 12000 h = 8000 Dmax = 245

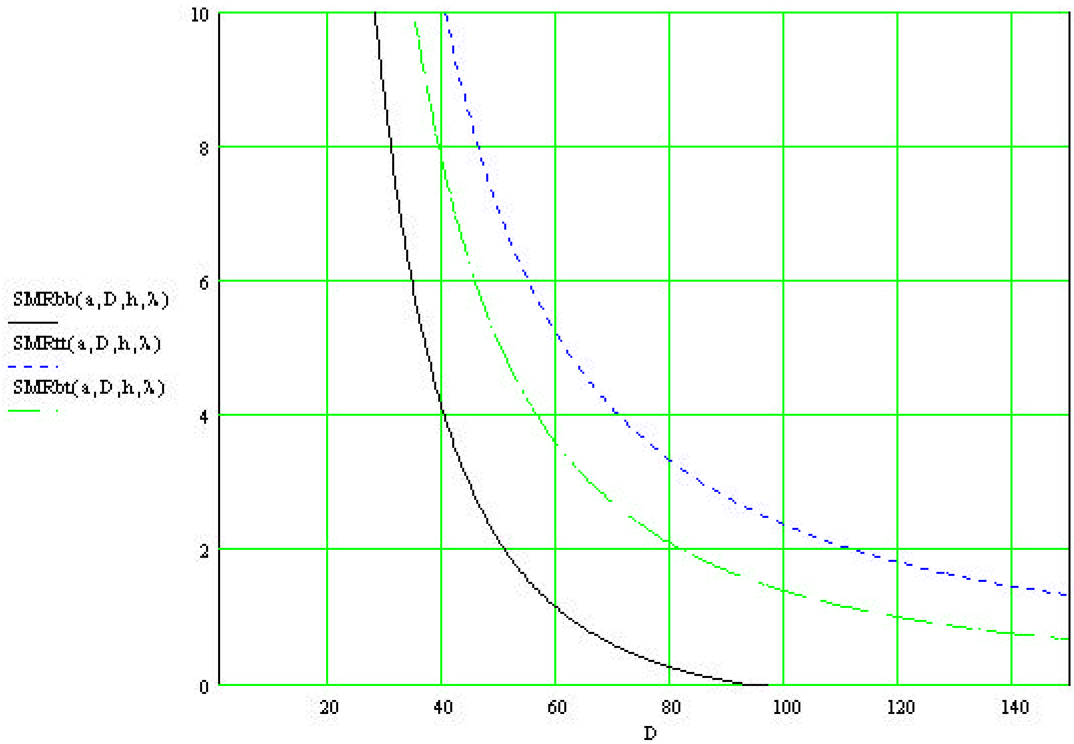


Figure 2-7(a) Signal-to-multipath ratios in dB vs separation in nm for various antenna combinations and the indicated flight altitudes

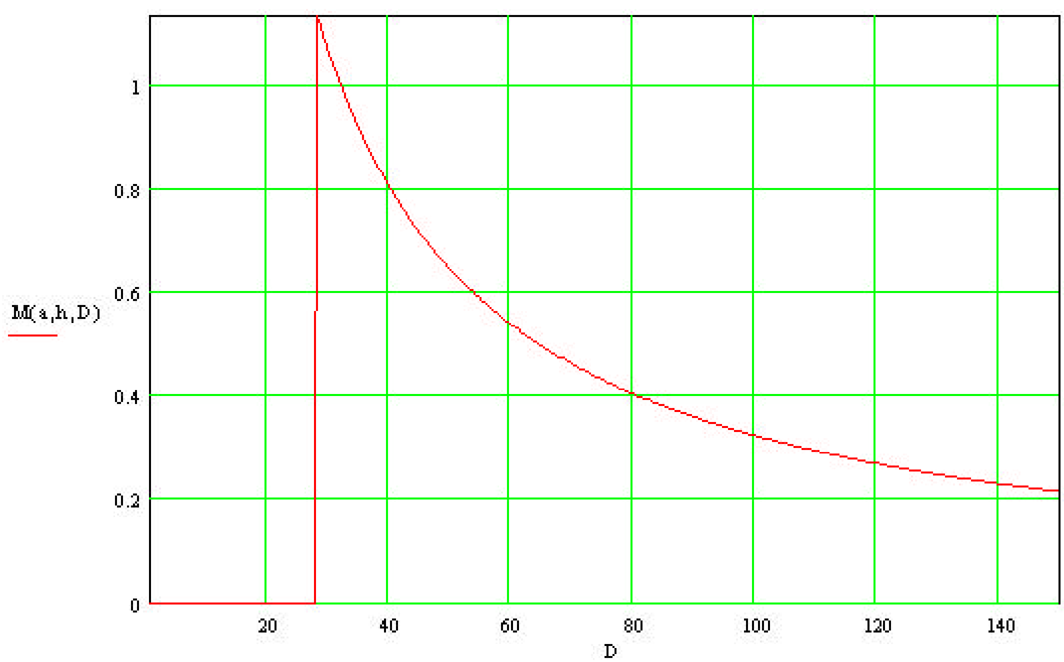


Figure 2-7(b) Multipath signal relative delay in usec vs separation in nm for values of bottom-bottom antenna pair SMRbb < 10 dB

F = 118   δ = 1   Gtd(0) = 0   Gbd(0) = 0   a = 12000   h = 8000   Dmax= 245

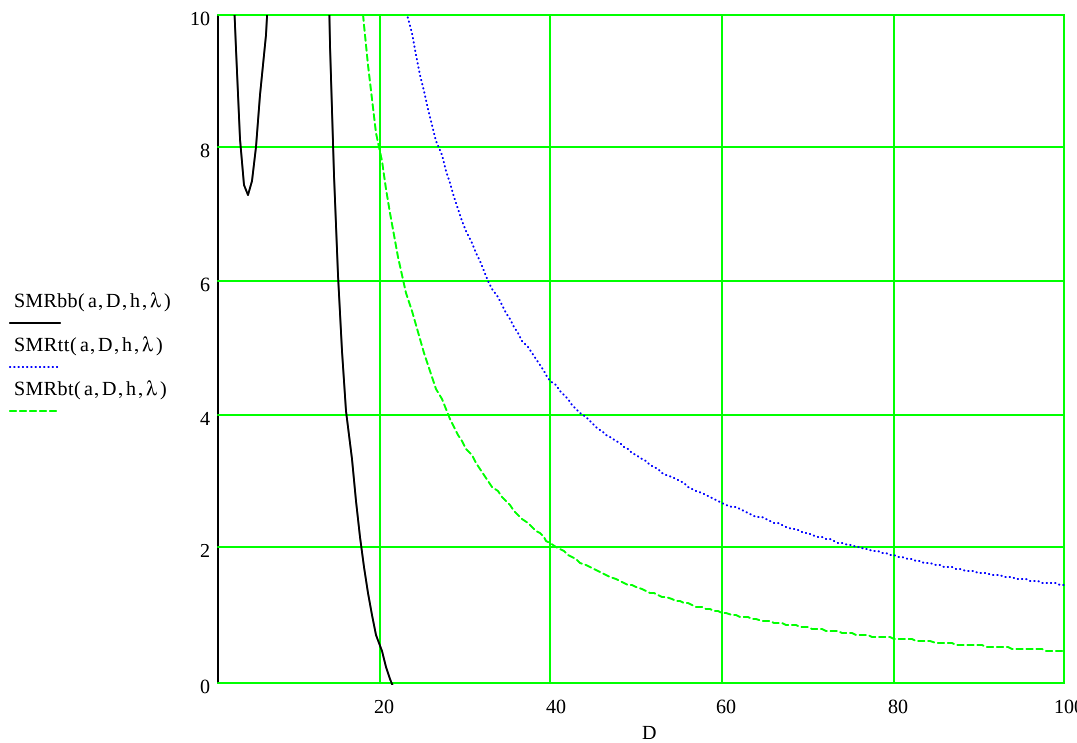


Figure 2-8 Signal-to-multipath ratios in dB vs separation in nm for various antenna combinations and the indicated flight altitudes

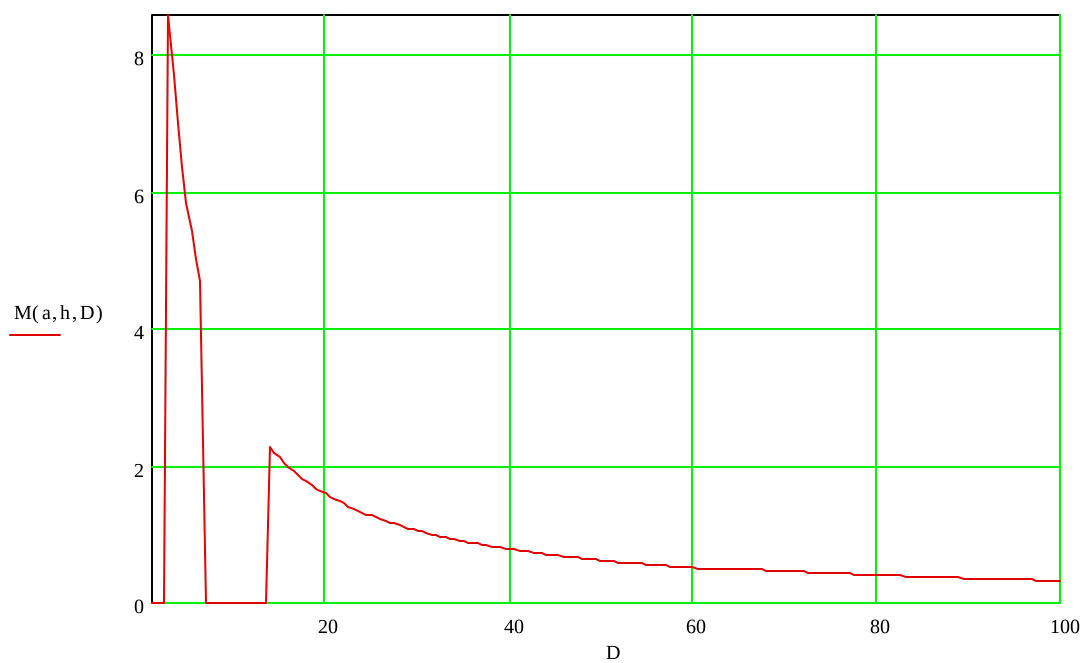


Figure 2-8 Multipath signal relative delay in usec vs separation in nm for values of bottom-bottom antenna pair SMRbb < 10 dB

3.0 AIR-to-GROUND RECEIVED SIGNAL LEVELS and SIGNAL-to-MULTIPATH RATIO (SMR)

Air-to-ground signal levels are examined in this section for an aircraft altitude of a feet and a ground antenna height of h feet. Ground reflectivity and aircraft top-bottom antenna gain patterns are the same as in section 2. As before, the process is first described for an assumed Extended Squitter frequency of 1090 MHz; typical results for UAT and VDL Mode 4 are then given.

3.1 Ground Antenna Pattern

Low traffic density 1090 MHz Extended Squitter ground sites and all UAT ground sites employ omni-directional DME antennas with an array height of about 6 feet. Elevation plane half power beamwidth for these arrays is 12 degrees with a peak gain slightly greater than 8 dBi. The peak of the beam is tilted above the horizon to reduce multipath and some pattern shaping is employed to provide fill in at high elevation angles. High angle fill in is not represented in this model, but lower angle general ground antenna characteristics and its multipath ground plane image are well described in the following model. Figure 3-1 shows the elevation plane beam tilted up 6 degrees with the half power point on the horizon. The dotted curve is the ground plane image used in multipath estimates.

Approximate array length, La, and half-power elevation plane beamwidth of ground omni-directional antenna:

$La := 6 \qquad \theta 3 := \frac{80 \cdot \lambda}{La} \qquad \theta 3 = 12$

Ground antenna gain vs elevation angle, ψ , for beam tilt of $\theta gp = \theta 3/2$:

$\theta g := 12 \qquad \theta gp := 6 \qquad \eta g := 0.7$ (η = 70% for csc-sq beam shape)

$$Gg(\psi) := \left(\frac{2}{\frac{\theta g}{57.3}} \cdot \eta g\right)^{0.5} \cdot \exp\left[-\left(1.174 \cdot \frac{\psi - \theta gp}{\theta g}\right)^2\right]$$

$$Ggd(\psi) := 20 \cdot \log(Gg(\psi)) \qquad Ggd(\theta gp) - Ggd\left(\theta gp + \frac{\theta g}{2}\right) = 3$$

$Ggd(0) = 5.3 \qquad Ggd(\theta gp) = 8.3$

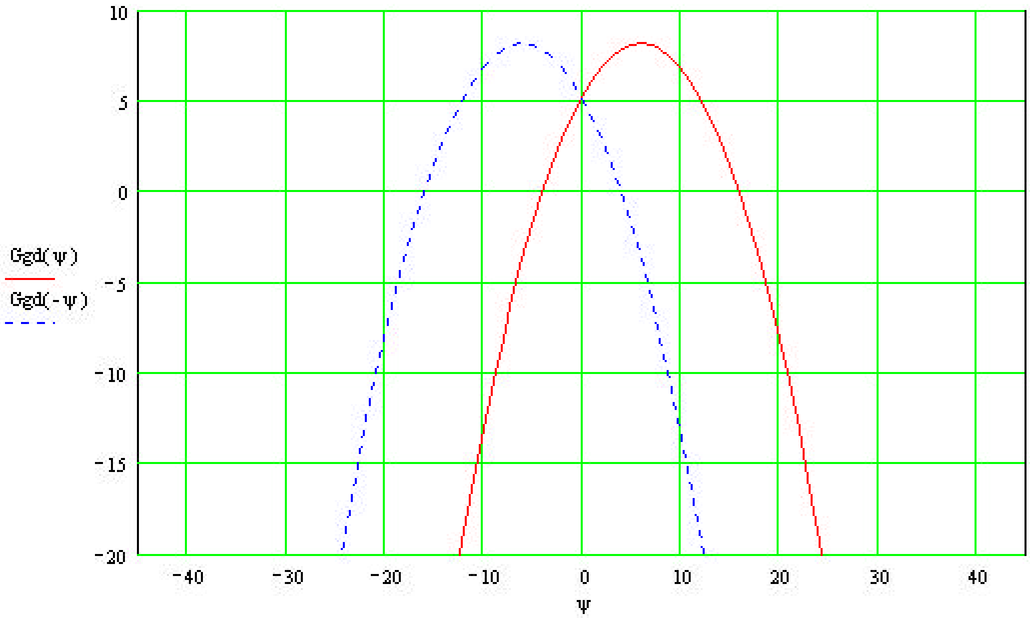


Figure 3-1 Assumed ground antenna free space elevation plane pattern (and its image for multipath calculations)

3.2 Ground Antenna Pattern in Elevation Plane Multipath Environment

The above elevation plane pattern and its image modified by the surface reflection coefficient produce an interference pattern for a mounting height h feet above the surface. This is derived in the following for our rough surface assumption of Figure 2-2. Notice the reduction in null depth with increased elevation angle in the resulting pattern plotted in Figure 3-2 for F = 1090 MHz. This is due to the shape of the under side of the beam and the rough surface reflection coefficient drop off at higher angles. Spacing between nulls depends upon the mounting height and the operating wavelength.

Ground antenna gain vs elevation angle, ψ, for height, h, above surface in multipath environment:

$h := 40 \qquad i := \sqrt{-1} \qquad \psi := 0, 0.01 .. 30 \qquad \beta o = \beta w \text{ or } \beta g$

$$gm(\psi, \delta, \lambda) := \left[Gg(\psi) + e^{i \cdot \left[(k) \cdot 2 \cdot h \cdot \sin\left(\frac{\psi}{57.3}\right) + \beta o(\psi) \right]} \cdot (m(\delta, \lambda, \psi)) \cdot Gg(-\psi) \right]$$

$Gm(\psi, \delta, \lambda) := | gm(\psi, \delta, \lambda) | \qquad Gmd(\psi, \delta, \lambda) := 20 \cdot \log(Gm(\psi, \delta, \lambda))$

h = 40 δ = 1 F = 1090 Gmd(0.4, δ , λ) = 10.6 Ggd(θgp) = 8.3

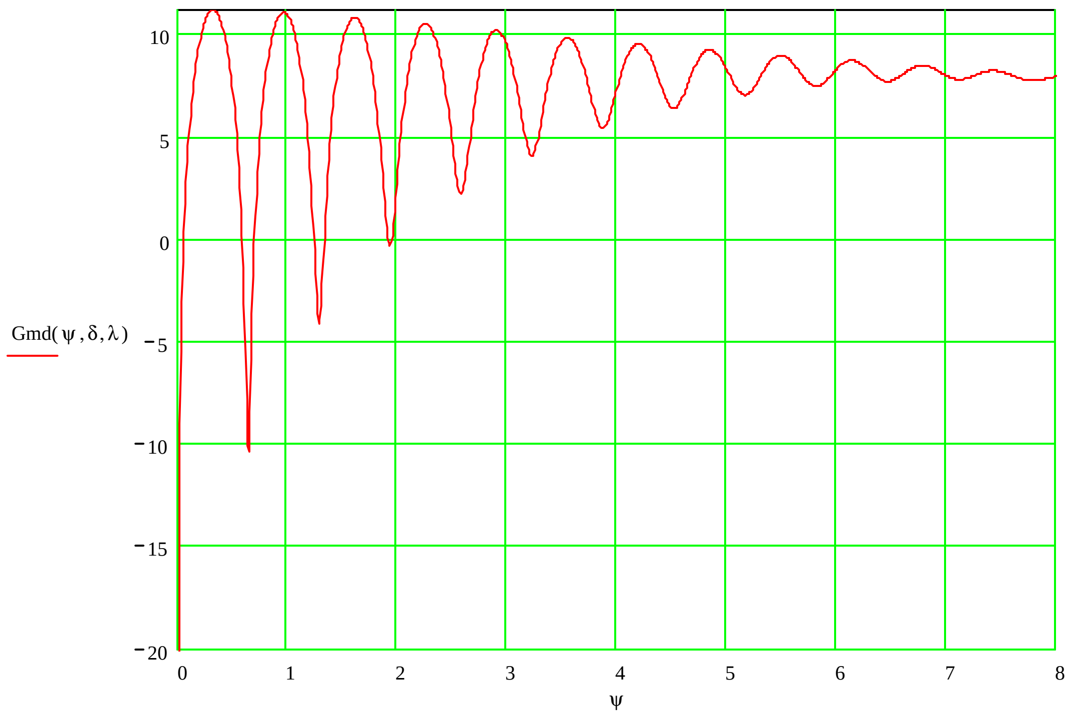


Figure 3-2 Elevation plane pattern with height, h, above reflecting surface and indicated parameters

3.3 Product of Air and Ground Antenna Patterns

With the above ground antenna pattern in the elevation plane interference environment and our top/bottom aircraft antenna patterns, we can now form the product of the transmit/receive antenna gains as a function of aircraft altitude, a, and lateral separation distance, D. The needed relationships are derived in the following for the usual flat earth approximation. Figure 3-3 illustrates the result for our current assumptions. The lower gain of the top antenna at higher elevation angles (shorter distances) is shown by the dotted curve. Elevation angle variation for our geometry is given in Figure 3-4. In this case, the angles are quite low until the aircraft is within about 10 nm of the ground site.

Product of aircraft and ground antenna gains vs elevation angle, ψ, in multipath environment:

$$Ggbd(\psi, \delta, \lambda) := Gmd(\psi, \delta, \lambda) + Gbd(\psi)$$

$$Ggtd(\psi, \delta, \lambda) := Gmd(\psi, \delta, \lambda) + Gtd(\psi)$$

For air-ground links, a>>h and a + h approximately equals a:

$a := 12000 \qquad los := 1.23\cdot\sqrt{a} \qquad los = 135 \qquad D := 1, 1.5 .. los$

$$\psi(a, D) := \operatorname{atan}\left[\frac{a - \left(\frac{D}{1.23}\right)^2}{D\cdot 6000}\right]\cdot 57.3 \qquad R(a, D) := \left[D^2 + \left(\frac{a}{6000}\right)^2\right]^{\frac{1}{2}}$$

$a = 12000 \qquad los = 135 \qquad h = 40 \qquad \delta = 1 \qquad \lambda = 0.9 \qquad Ggd(\theta gp) = 8.3 \qquad \theta gp = 6$

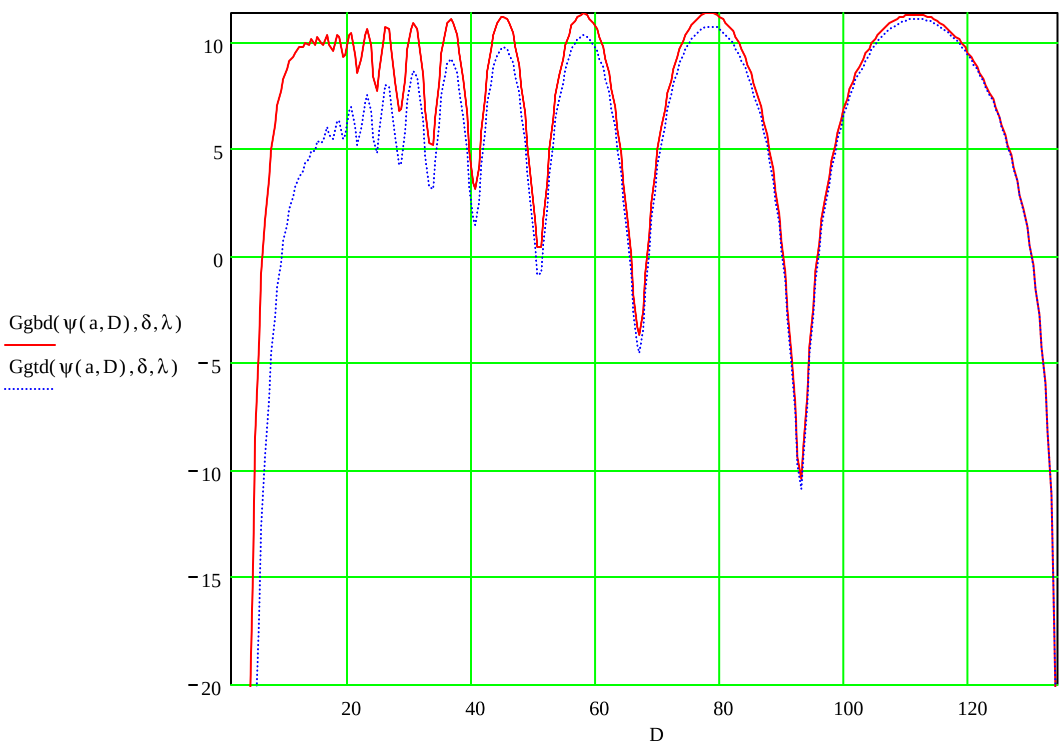


Figure 3-3 Product of aircraft and ground antenna gains vs distance,D, in multipath environment for indicated parameters

a = 12000 los = 135

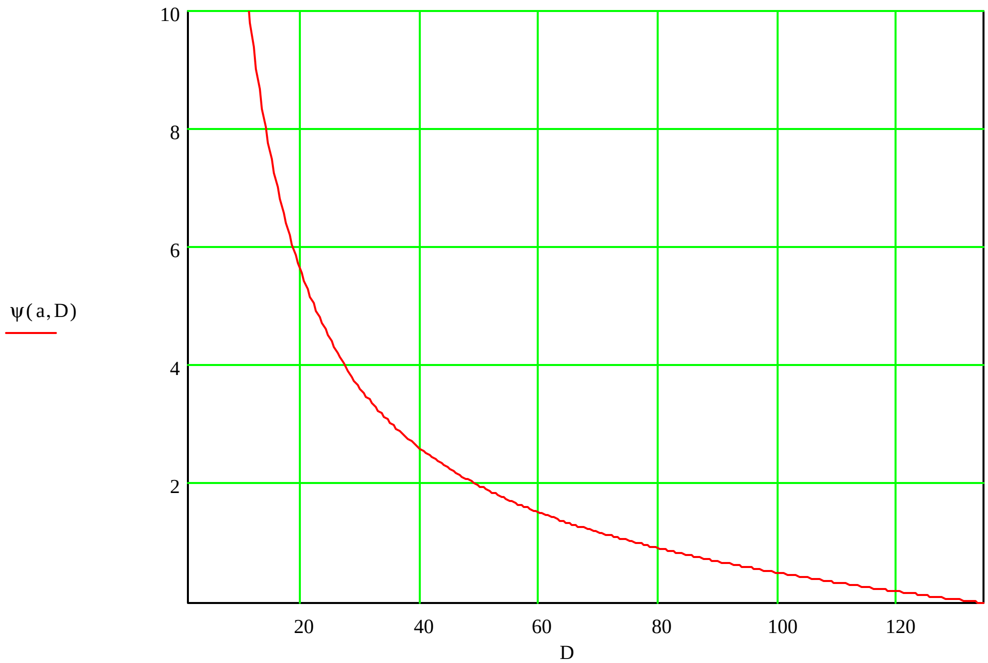


Figure 3-4 Elevation angle, ψ, vs distance, D, for altitude, a.

3.4 Received Signal Levels

Use of link budget parameters with the relationships derived above yield the expected received signal level variation for top/bottom aircraft antennas over a constant altitude approach to the ground site. For reference, the estimate made by assuming an aircraft antenna gain of 0 dBi and the peak ground antenna gain in a non-multipath environment is given by P0Gd.

Figure 3-5 results with our assumed 1090 MHz Extended Squitter transmit power, Ptd = 54 dBm at the antenna, and a receiver MTL = -84 dBm. A feed line loss of 2 dB is included for the ground facility. For these conditions, interference nulls cause the received signal to drop out at 90-95 nm and at about 65 nm. The actual csc-squared DME pattern shape should improve performance compared with that shown at very close distances.

Figure 3-6 is a similar plot for UAT values of Ptd = 50 dBm, MTL = -92 dBm, and Ld = 2 dB for feed line loss. Again the received signal drops below MTL at around 90 nm as shown in the figure, but the increased link margin avoids the second null fade at 60 nm.

Received signal level in dBm as a function of distance,D, in nmi:

$Pw := 250 \qquad Ptd := 10 \cdot \log(Pw) + 30 \qquad Ptd = 54 \qquad Ld := 2 \qquad MTL := -84$

$$Pgbd(a, D, \delta, \lambda) := (Ptd + Ggbd(\psi(a, D), \delta, \lambda)) - \left[37.5 + \left(20 \cdot \log(R(a, D)) + 20 \cdot \log\left(\frac{984}{\lambda}\right)\right)\right] - Ld$$

$$Pgtd(a, D, \delta, \lambda) := (Ptd + Ggtd(\psi(a, D), \delta, \lambda)) - \left[37.5 + \left(20 \cdot \log(R(a, D)) + 20 \cdot \log\left(\frac{984}{\lambda}\right)\right)\right] - Ld$$

$$P0Gd(a, D, \delta, \lambda) := (Ptd + Ggd(\theta gp)) - \left[37.5 + \left(20 \cdot \log(R(a, D)) + 20 \cdot \log\left(\frac{984}{\lambda}\right)\right)\right] - Ld$$

Received signal level in dBm as a function of distance,D, in nmi:

$Gbd(0) = 0 \qquad Ggd(\theta gp) = 8.3 \qquad \theta gp = 6 \qquad F = 1090 \qquad Ptd = 54 \qquad Ld = 2$

$a = 12000 \qquad h = 40 \qquad \delta = 1 \qquad los = 135$

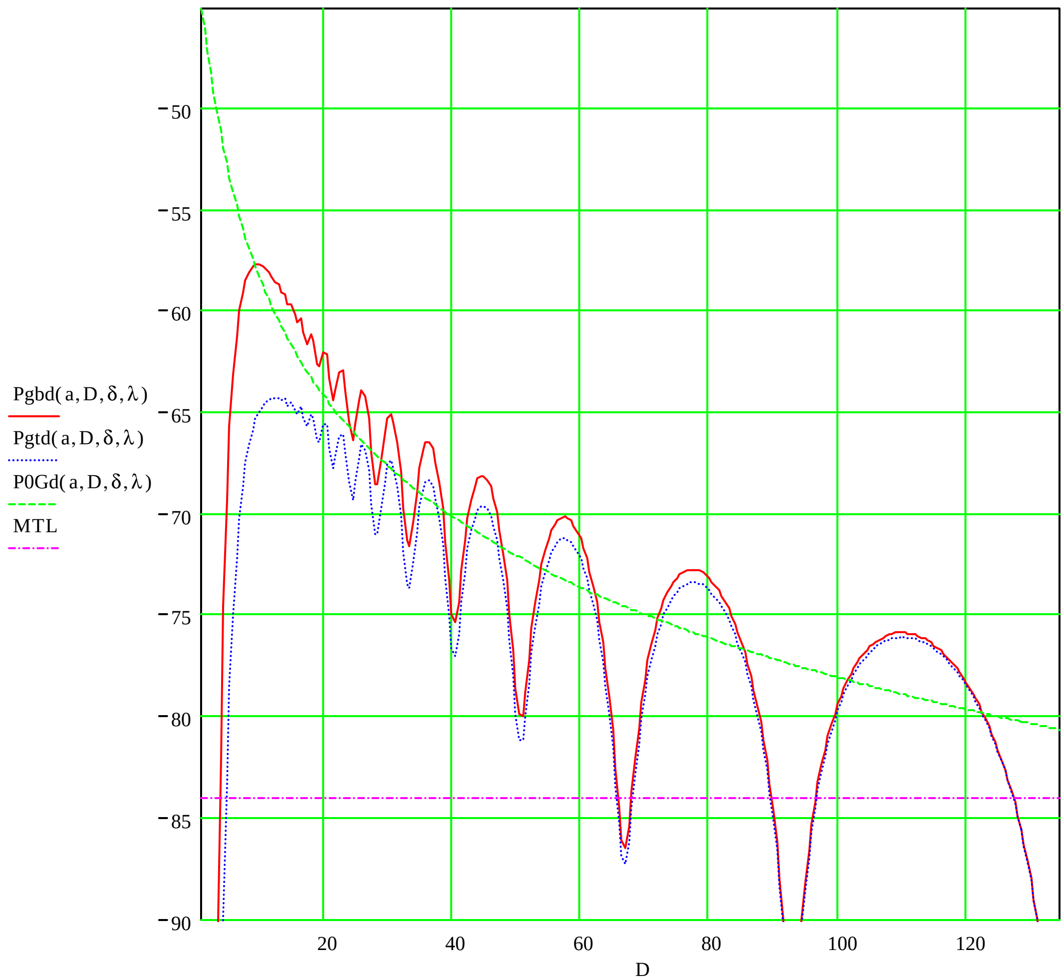


Figure 3-5 Received signal level (dBm) vs range (nmi) for air-ground link and indicated parameters. Solid line is bottom aircraft antenna, dashed line is top aircraft antenna. Dashed curve is for 0 dBi aircraft gain and peak gain for the ground antenna.

Received signal level in dBm as a function of distance,D, in nmi:

Gbd(0) = 0 Ggd(θgp) = 8.3 θgp = 6 F = 981 Ptd = 50 Ld = 2

a = 12000 h = 40 δ = 1 los = 135

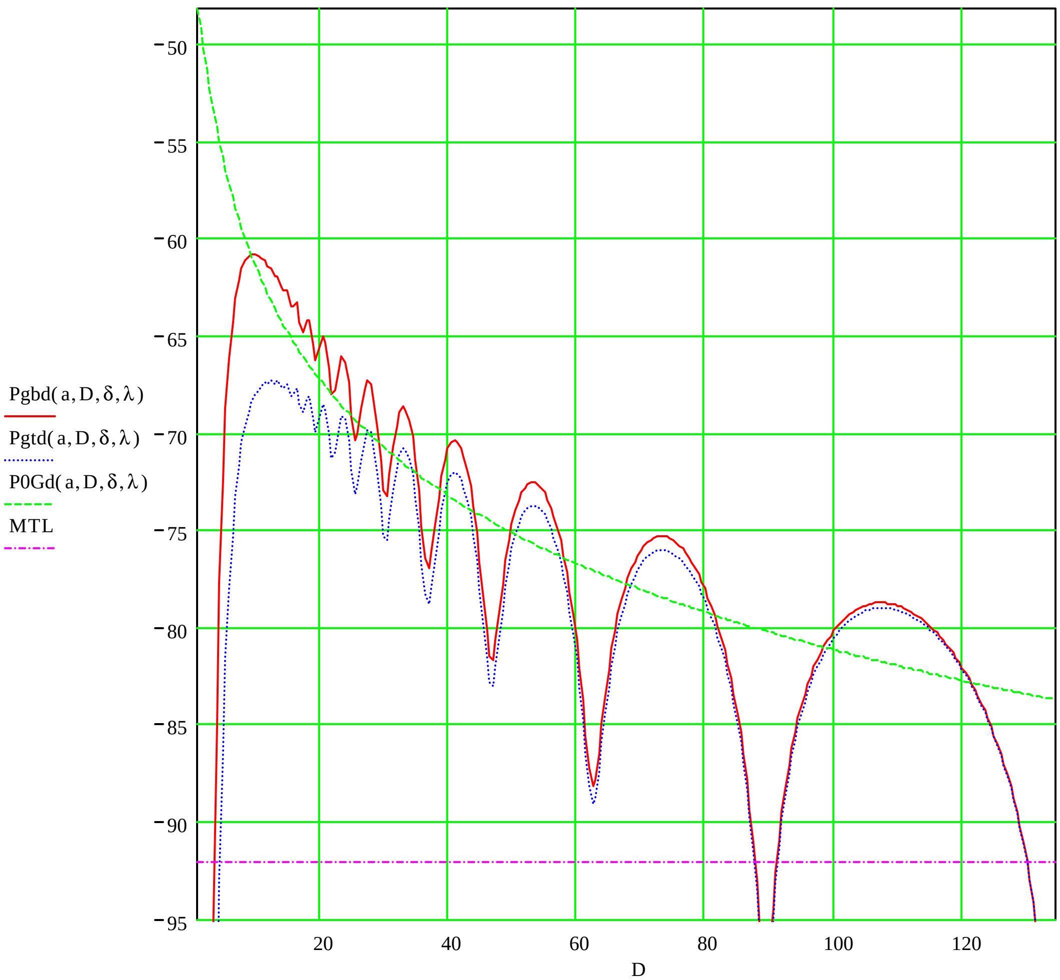


Figure 3-6 Received signal level (dBm) vs range (nmi) for air-ground link and indicated parameters. Solid line is bottom aircraft antenna, dashed line is top aircraft antenna. Dashed curve is for 0 dBi aircraft gain and peak gain for the ground antenna.

Signal variation at VHF is, as expected, somewhat different than air-ground signal characteristics at L-band. First, as noted in section 2.0, the assumed rough ground surface height variation of 1 foot looks like a smooth surface at VHF. Second, the 6 foot long ground antenna produces the broad beamwidth gain pattern shown in Figure 3-7. Finally, the 40 foot mounting height is only about five wavelengths at 118 MHz and this has an associated broadening of the interference pattern null widths. The aggregate effect of all this is shown in Figure 3-8 for VDL Mode 4 link parameters of Ptd = 40 dBm, receiver MTL = -98 dBm, and a 2 dB feed loss. Differences in this model and the usual estimate are shown to be most apparent at low elevation angles.

Ggd(0) = −0.8   Ggd(θgp) = 2.2

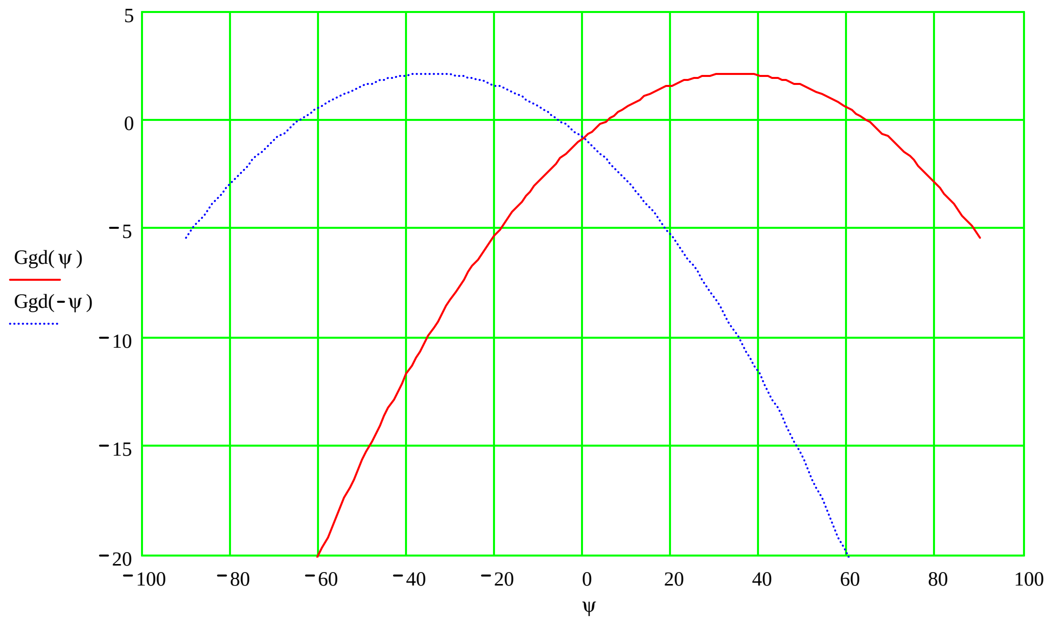


Figure 3-7 Assumed ground antenna free space elevation plane pattern (and its image for multipath calculations)

Gbd(0) = 0 Ggd(θgp) = 2.2 θgp = 34.74 F = 118 Ptd = 40 Ld = 2

a = 12000 h = 40 δ = 1 los = 135

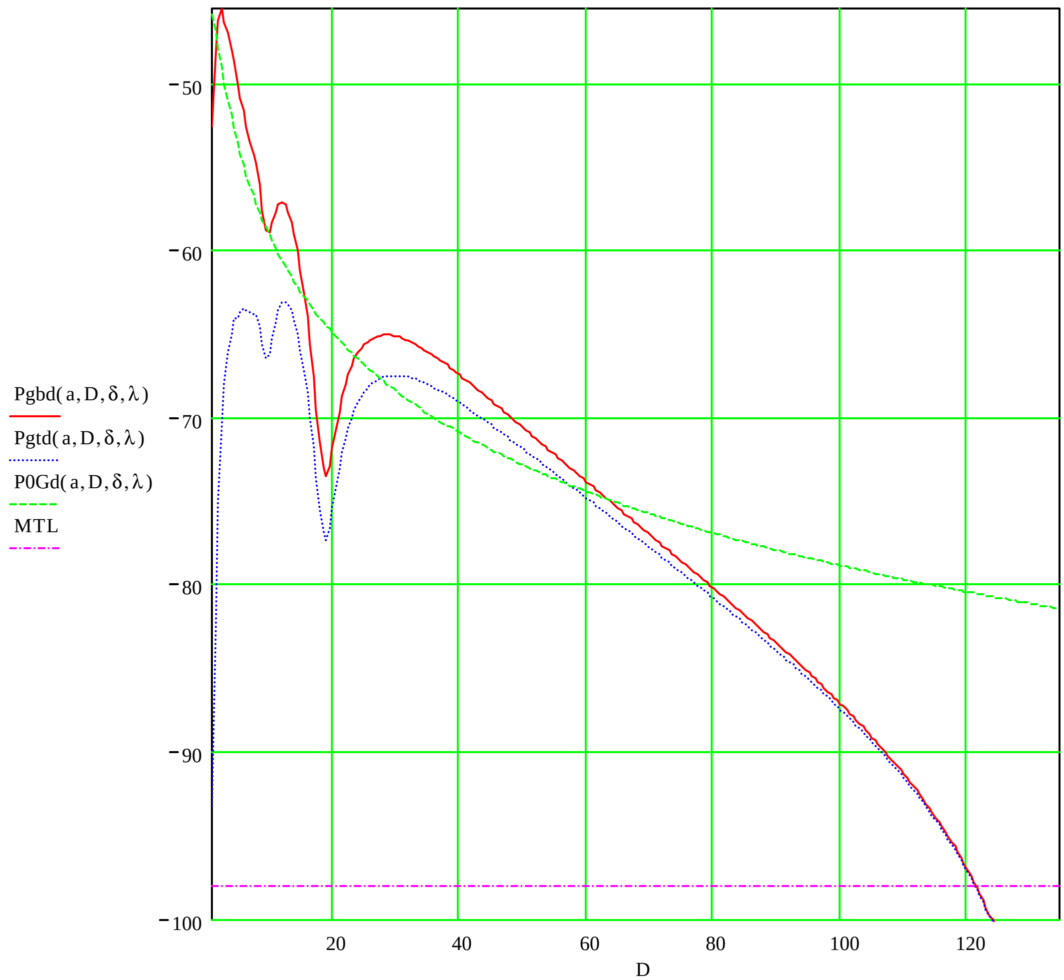


Figure 3-8 Received signal level (dBm) vs range (nmi) for air-ground link and indicated parameters. Solid line is bottom aircraft antenna, dashed line is top aircraft antenna. Dashed curve is for 0 dBi aircraft gain and peak gain for the ground antenna.

4.0 Azimuth Plane Multipath

Azimuth plane multipath is of primary interest in airport surface operation or in approaches to the runway threshold. Issues related to multipath in such cases are examined here for transmit-reflection-receive configurations leading to a fixed value of multipath delay. The Tx-Rx baseline, Ro, is assumed to be 1 nm and the reflector of a specified bi-static cross section is moved on an elliptical curve with foci at the Tx-Rx locations. The example used here is for a fixed delay of 0.5 usec since this could cause decode problems for L-band systems if the resulting SMR is low enough. The analysis uses standard radar formulation of the multipath signal subject to the constraint that the sum of the multipath delay is constant. Variations given are in terms of the angle from the receiver to the reflector measured from the Tx-Rx baseline.

Azimuth plane multipath geometry:
Ro = Tx-Rx separation in nm
Rt = Tx-reflector separation in nm
Rr = reflector-Rx separatio in nm
S = Rt + Rr
ϕ = included angle btwn Ro and Rr
M = multipath delay in usec
S = Ro + M/6

$M := 0.5$ usec $\quad d := \frac{M}{6} \cdot 6000 \quad d = 500$ feet $\quad Ro := 1$ nm $\quad \sigma := 1 \cdot 10^6$ sq-ft

$$S(Ro, M) := Ro + \frac{M}{6} \qquad Rr(Ro, \phi, M) := \frac{S(Ro, M)^2 - Ro^2}{2 \cdot (S(Ro, M) - Ro \cdot \cos(\phi))}$$

$$Rt(Ro, \phi, M) := S(Ro, M) - Rr(Ro, \phi, M) \qquad \phi := 0, 0.001 .. \pi$$

$$SMR(Ro, \phi, M) := 10 \cdot \log\left(\frac{4 \cdot \pi \cdot 6000^2}{\sigma} \cdot \frac{Rt(Ro, \phi, M)^2}{Ro^2} \cdot Rr(Ro, \phi, M)^2\right)$$

$$F(Ro, \phi, M) := \frac{(Rt(Ro, \phi, M)) + Rr(Ro, \phi, M)}{Ro}$$

Jumbo jet radar cross section appxoximately 1000 sq ft

Flat panel and cylinder cross sections:

$F := 1090 \quad \lambda := \frac{984}{F} \quad \lambda = 0.9$

x = flat panel width & y = height in feet

$x := 20 \quad y := 20 \quad \rho := 0.5$

$$\sigma s := 4 \cdot \pi \cdot \frac{(x \cdot y)^2}{\lambda^2} \cdot \rho \qquad \sigma s = 1.234 \cdot 10^6$$

$$bw := \frac{1.2 \cdot \lambda}{x} \qquad s := Ro \cdot bw \qquad s = 0.054$$

cylinder ht = h feet, radius = a feet

$h := 30 \quad a := 100 \quad \rho := 0.5$

$$\sigma c := 2 \cdot \pi \cdot \frac{h^2 \cdot a}{\lambda^2} \cdot \rho \qquad \sigma c = 3.469 \cdot 10^5$$

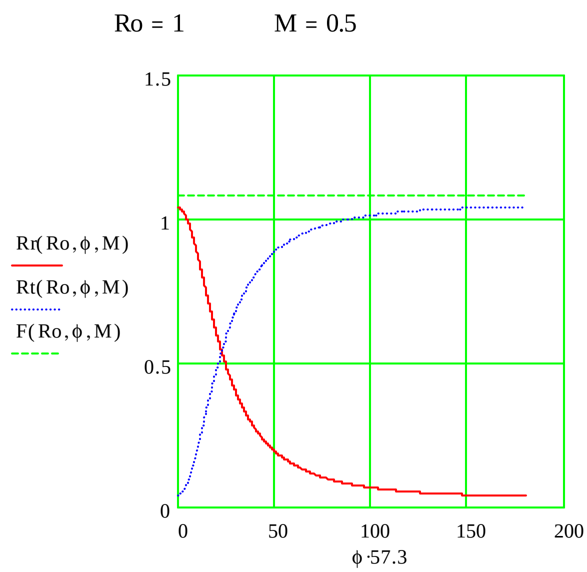


Figure 4-1 Variation of Tx and Rx ranges to reflector, and their ratio for indicated values of Ro nm and M usec multipath delay

Figure 4-1 shows the geometrical variation in terms of the subtended angle to the reflector. Radar cross sections for even large aircraft do not exceed about 1000 square feet, but large flat building panels could produce high cross sections over narrow spectral angular widths. Figure 4-2 shows the resulting SMR for such a surface oriented to produce such a 10^6 square foot cross section at L-band when situated at various points on the 0.5 usec delay ellipse. Both Tx and Rx antennas are assumed to be omni-directional. Even in this extreme example, low SMRs occur only when the reflector is near the transmitter or receiver and their alignment is normal to the surface. The same building panel at VHF scatters over a wider angular width, but the cross section in this case is only on the order of 10^4 sq-ft and the SMR at VHF is much better as shown in Figure 4-3.

$\sigma = 1 \cdot 10^{6}$ $M = 0.5$ $Ro = 1$

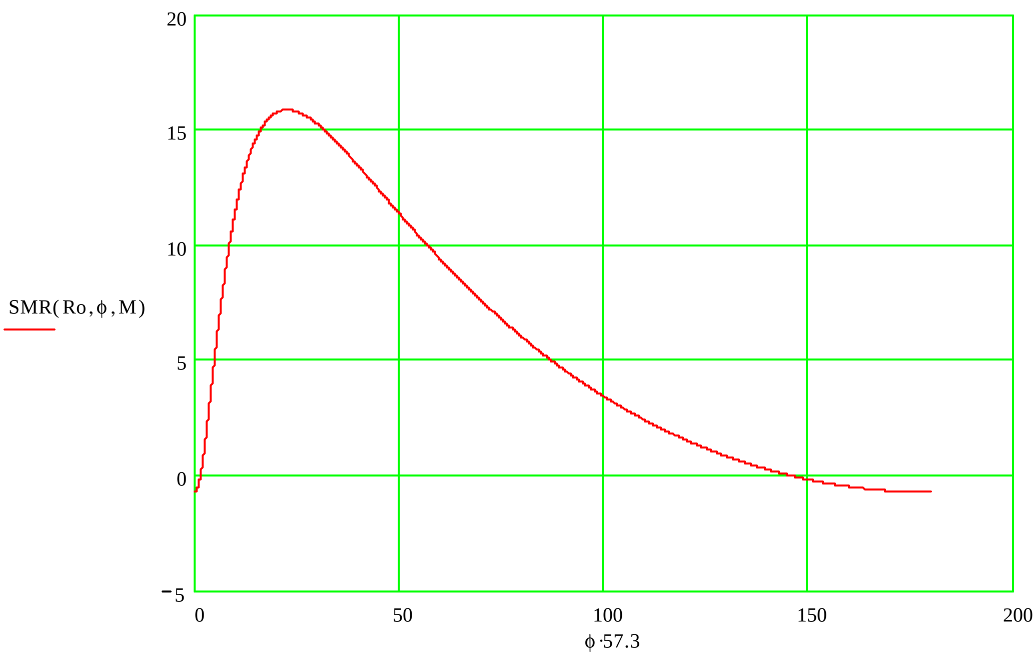


Figure 4-2 Variation of SMR in dB vs baseline angle from receiver to reflector for indicated Tx/Rx separation, multipath delay, and bi-static cross section

$\sigma = 1.5 \cdot 10^4$ M = 0.5 Ro = 1

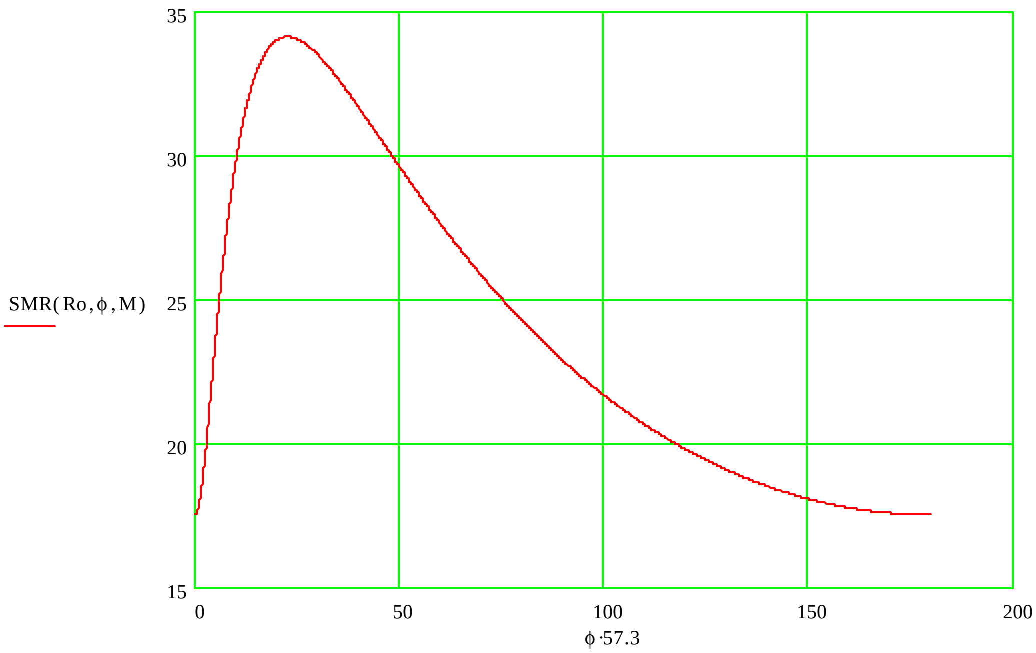


Figure 4-3 Variation of SMR in dB vs baseline angle from receiver to reflector for indicated Tx/Rx separation, multipath delay, and bi-static cross section

5.0 Summary

Link performance sensitivity to antenna gain variations and multipath have been examined for air-air, air-ground, and airport surface operations. For the nearly co-altitude air-air example, antenna fading for any combination of top/bottom Tx/Rx antennas was apparent only at very short ranges where the link fade margin was greatest. SMRs were low at long separations in this example and multipath delays could lead to decode problems for L-band systems. These same delays tend to produce signal level modification in VHF systems. Both L-band systems and the VHF system were limited by line of sight for the 12000 ft altitude example of air-ground operation with interference lobes also producing a brief fade at around 90 nm at L-band. Horizontal plane multipath on the airport surface produces the lowest SMRs when the reflector is very near either the transmit or receive omni-directional antenna. The SMR at VHF is much better than that at L-band for the same geometry and reflector size.

Appendix N

Areas for Potential Further Study

Appendix N.1 Multipath Effects

Transmissions of ADS-B signals mainly propogate directly from the transmitter to the receiver. It is also possible for a portion of the signal to take a different path, arriving at the receiver at a slightly different time (later than the direct reception). This is a common condition for the air-to-air signals and on the airport surface. Often the unwanted multipath is much weaker, but strong multipath and serious degradation can occur in some cases. Modeling the relative power of multipath is difficult, and was not included in the TLAT simulations.

In the development of air-to-air TCAS, multipath caused by reflection from the ground (or water) was found to be a significant issue. An air-to-air measurement program focusing on multipath was undertaken by the FAA early in the TCAS program. The results, which are documented in Reference 1 of this Appendix, indicate how relative multipath powers depend on altitude, geographical location, and antenna top-bottom combinations.

In most cases the multipath delay is about 3 microseconds or less. For 1090 MHz Extended Squitter and UAT, where the duration of one bit is 1 microsecond, the multipath timing causes a degradation, depending on relative power. VDL Mode 4 is different and has a significant advantage in this respect. Because the bit duration (50 microseconds) is much longer than the multipath delay, the net effect is essentially a change in signal amplitude, not a distortion of signal shape. This benefit has been observed in testing on the airport surface.

Testing of 1090 MHz Extended Squitter signals on an airport surface has also been conducted. The results (Reference 2 of this Appendix) indicate that to achieve reliable reception from aircraft to a ground system requires a number of receiving antenna installations (four or five for an airport the size of Logan Airport in Boston).

Given that multipath is difficult to model accurately, and that it was not included in the TLAT simulation, actual measurements are particularly important. Measurements have been collected in a variety of conditions: airborne testing at the Eurocontrol Experimental Center; testing in the Gulf of Mexico (Reference 7 of Appendix F), testing in Alaska, testing at Atlanta (Reference 9 of Appendix F), measurements in Los Angeles (Reference 17 of Appendix F), measurement at the FAA Technical Center; and measurements in Frankfurt, Germany (Reference 19 of Appendix F). These data could be the basis for further analysis.

References

1. A. Paradis, “L-Band Air-to-Air Multipath Measurements,” Lincoln Laboratory technical report, ATC-76, June 1977.
2. M. L. Wood, “Mode S Beacon Signals on the Airport Surface,” Lincoln Laboratory Journal, vol. 2, no. 3, fall 1989.

Appendix N.2 Propagation in VDL Mode 4

The VDL Mode 4 system description calls for retriggering, which is assumed in SPS to some extent, since it focuses on slots rather than times of arrival. The case of interest to the TLAT was that of a distant (low signal) transmitter occupying a slot, followed by a nearby (high signal) transmitter in the subsequent slot.

If the distant transmitter is more than 205 nautical miles further away than the nearby transmitter (guard time), the messages will overlap and the distant transmission should not be received, since it will be interfered with by a stronger signal. SPS only looks at slots, disregarding the potential of slot overrun, thus ignoring the possibility that the nearby signal in the next slot would affect the earlier distant one. It would record the distant transmission as being received (in the absence of interference in its slot).

In order to determine the magnitude of the problem, the TLAT examined the results from the LA Basin 2020 Global Signalling Channel, which is the worst case for slot occupancy. The cases consisted of the following:

1. A slot with a transmitter having a probability of successful message receipt greater than 0.2, followed by
2. A slot with a transmitter at least 205 nmi closer than the transmitter in the previous slot, no matter its probability of successful message receipt. (It could be interfered with, but this doesn't matter. It is the signal level that counts.)

This situation occurs a minimum 1.4% of the time at the victim receiver in the center of the scenario. Recall that, for purposes of the assessment, aircraft which are this distant are of no interest as far as the evaluation criteria are concerned, but there could an effect on the slot reservation tables in the simulation. This would presumably provide an optimistic picture of the ability to choose a free slot, although it can certainly be argued that a 1.4% effect is far smaller than other uncertainties.

Appendix N.3 Range Limit of Core Europe Scenario[1]

The Core Europe 2015 traffic scenario covers a circular region of radius 300 nmi centered around Brussels. This area includes five major TMAs (London, Paris, Amsterdam, Brussels, and Frankfurt), three of which lie close to the inner area border (200 nmi), notably Frankfurt, Paris, and London. ADS-B link performance was evaluated for victim receivers close to the center of the scenario, in order to minimise the impact of the scenario border.

In the case of VDL-4 it can be argued that the aircraft outside the scenario border 300 nmi might have an impact even for a victim receiver at Brussels because remote aircraft could affect the reservation patterns of targets at intermediate distances. The impact of remote aircraft was evaluated by considering an extended Core Europe 2015 with radius=400 nmi, where 400 aircraft were added in the external ring from 300 to 400 nmi. All these aircraft were set to be A2/A3 and were placed at altitudes between FL 410 and FL100 in order to maximise their Line of Sight range. The TLAT simulation results showed that those aircraft did not have a noticeable impact on the reception performance seen by any victim receiver in the range 0-100 nmi from the scenario centre.

It is important to note however that

- the Core Europe 2015 as used by the TLAT would not be appropriate for evaluating performance at distances beyond 100 nmi from Brussels. Therefore Core Europe 2015 is not sufficient for evaluating performance above Frankfurt, Paris or London. In order to study such cases it will be necessary to expand this scenario.
- the VDL-4 channel management scheme assessed in the TLAT simulations would have to be optimised concerning the coverage of the two Regional Signalling Channels. These were set to be semicircles around Brussels (with radius 175 nmi), but it may well be that there exist more efficient arrangements.
- Core Europe extends well beyond the Core Europe 2015 scenario borders. It will be necessary to check whether a two channel configuration would suffice for Core Europe areas outside the Core Europe 2015 inner area. It is possible that additional Regional Signalling Channels may be needed. The restriction to four receivers for all aircraft means that any additional Regional Signalling Channel has to separated by at least 100nmi from the two Regional Signalling Channel in Core Europe 2015. The development of an extended Core Europe 2015 would be indispensable for the study of this issue.

[1] A similar case can be made for the Los Angeles Basin 2020 Scenario.

Appendix N.4, Multi-link Considerations

The terms of reference for the TLAT state that the technical link evaluation criteria should consider the "technical aspects of the use of multiple ADS-B situational awareness links for different aircraft types and in different airspace types, identifying any technical advantages/disadvantages and outstanding issues." The FAA and MITRE/CAASD are currently conducting a survey of manufacturers to assess the technical feasibility and cost viability of a multi-link ADS-B solution.

Additionally, if a multi-link solution is to be implemented, the aviation community must define the necessary standards. Currently, there is no standards setting organization developing requirements for a multi-link solution.

Appendix N.5 Co-site interference

The co-site interference issue is dependent on primarily the antenna isolation or decoupling values that will vary as a function of aircraft types (size, etc) and the location of the antennas on the individual types of aircraft. Other factors such as frequency separation and transmit power are also important. The TLAT has not been able to fully assess the potential co-site interference issues related to VDL Mode 4 since work concerning the frequency planning criteria is on-going in the ICAO AMCP Working Group B but not yet finalized, and the fact that it is an implementation specific issue. However, it is assumed that the frequency planning criteria and antenna isolation techniques on the aircraft can mitigate this problem

Appendix N.6: Terrain Effects

With respect to the 1090 MHz Extended Squitter, terrain effects were included in the TLAT simulations for LA Basin and Core Europe to permit validation through comparison with field data. To help understand the effects of terrain the LA Basin scenario was also simulated without terrain, and the results showed that terrain has a significant effect. The altitude distribution in the original TLAT scenarios was the same in all locations, which therefore was unrealistic when terrain is included (aircraft were defined in locations below ground level). To resolve this discrepancy the traffic scenarios were modified to add the terrain elevation to the original aircraft altitudes for all aircraft in the scenario.

An assessment of VDL Mode 4 performance involves, among other issues, consideration of an effect called "hidden terminals." Figure N.6-1 illustrates conditions in which hidden-terminal effects could occur. Aircraft A and C are prevented from communicating with one another by the intervening terrain. Thus it is possible for Aircraft A and C to decide to broadcast in the same slots, thus causing garbling of their information as received by Aircraft B which can see both aircraft. Although it would have desirable to include such terrain effects in the VDL Mode 4 simulation, the tool used for VDL Mode 4 simulation did not include terrain and any increase in hidden terminal effects that such terrain might introduce. Also, any elements of the VDL Mode 4 system definition that might mitigate these effects was not included in the VDL Mode 4 simulations. Assessment of terrain effects must be considered in implementation planning for VDL Mode 4 and has not been fully addressed by the TLAT.

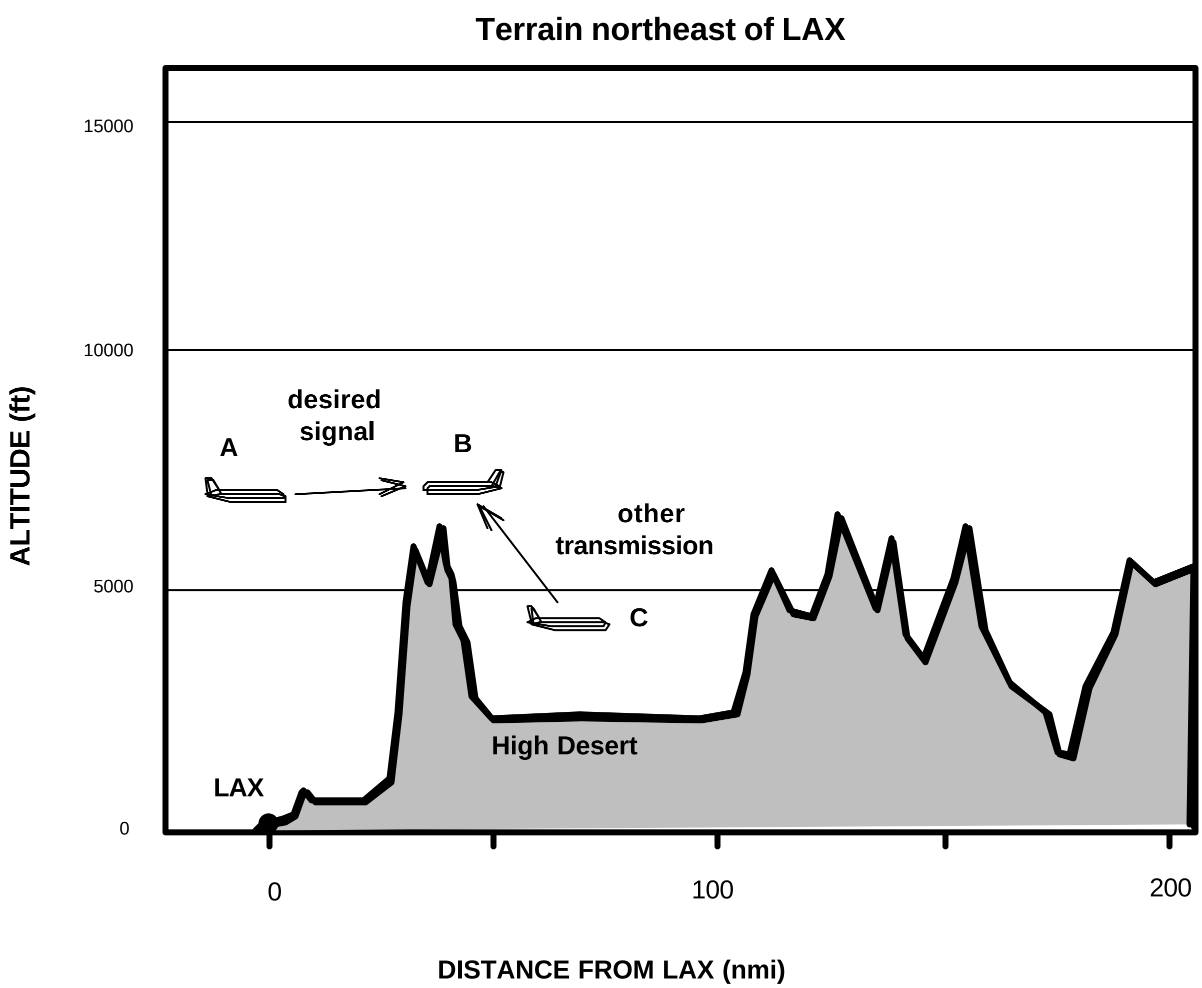


Figure N.6-1. Terrain Effects

Appendix N.7: "Honeycomb" Channel Management Scheme for VDL Mode 4

An alternative channel management proposal for the Los Angeles 2020 scenario, termed the "honeycomb" scheme, was examined by the TLAT (see Appendix M.1). While the honeycomb scheme as proposed in preliminary form did not address all necessary system aspects pertinent to its implementation, the scheme had the advantage of potentially requiring fewer frequencies and avionics with fewer ADS-B receivers.

The analysis of the honeycomb scheme was incomplete at the time of this report. However, it was possible to conclude that there is as yet no evidence that the honeycomb scheme as proposed improves VDL Mode 4 performance when compared to the channel management scheme simulated by the TLAT for the Los Angeles 2020 scenario. Further refinement of the honeycomb plan may result in improved performance, but the extent of modifications that would be required is not clear.